# Slope effect on costs and productivity of single-grip purpose-built and excavator based harvesters

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## DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it any university for degree.

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## ABSTRACT

In this study a mechanised *Eucalyptus* pulpwood cut-to-length harvesting operation comprising felling, debarking, debranching and cross cutting of assortments, was observed using time studies to determine the effect of slope on harvester productivity and cost of wood production. Time studies and data analysis was done according to the South African Forestry time study standard and machine costs according to the South African Harvesting and Transport Costing Model. Two different types of harvesting machines were studied; an excavator based machine, Volvo EC210BF, and a purpose built levelling machine, TimberPro TL725B, both fitted with Maskiner SP 591 LX harvester heads. A single operator with significant experience and training on both machines was used throughout the duration of the study. The machines were observed harvesting on a range of slopes, from level to 50% in two separate work corridors with relatively similar trees in terms of individual tree volume and form. The species studied was a *Eucalyptus grandis x camaldulensis clone*. Continuous slope data, as opposed to slope categories, for each position at which the harvesters would position themselves to undertake harvesting and processing, was derived using large footprint LiDAR data of the area. The purpose built harvester was levelling enabled as opposed to the Volvo which was not. Apart from differences in mass, the Volvo was not modified for forestry work and the booms were on different sides of the particular machine. Cost calculations were carried out on each machine to determine which machine was more cost effective. The study design was a 2 x 2 factorial design with two treatments (machine type) against slope and individual tree volume as factors.

The results indicate that the productivity of the excavator based machine decreased by $0.048m^3.PMH^{-1}$ for every 1% increase in slope. The purpose built machine was not significantly affected by slope in this study and maintained an average productivity regardless of extreme slope. The purposed built machine was found to have a higher mean productivity (16.24 $m^3.PMH^{-1}$) than the excavator based machine (13.00 $m^3.PMH^{-1}$), but this extra productivity came at a price, as the excavator based machine was more economical per cubic metre. The mean harvest cost for the purpose built machine was found to be $R122.67.m^{-3}$ whilst the excavator based machine achieved a mean cost of $R94.46.m^{-3}$.

## ABSTRAKTE

In hierdie studie 'n gemeganiseerde Eucalyptus pulphout cut-to-lengte oes werking bestaande afkap, ontschorsing, debranching en kruis sny van ruimtes, is waargeneem met behulp van tyd studies aan die effek van helling op stroper produktiwiteit en koste van hout produksie te bepaal. Tyd studies en data-ontleding is gedoen volgens die Suid-Afrikaanse Bosboumaatskappy tyd studie standaard en masjien koste volgens die Suid-Afrikaanse oes en vervoer kosteringsmodel. Twee verskillende tipes snymasjiene bestudeer; 'n graaf gebaseer masjien, Volvo EC210BF, en 'n doelgeboude nivellering masjien, TimberPro TL725B, toegerus met Maskiner SP 591 LX stroper koppe. 'N Enkele operateur met 'n groot ervaring en opleiding op beide masjiene gebruik regdeur die duur van die studie. Die masjiene is waargeneem oes op 'n verskeidenheid van hange van vlak tot 50% in twee afsonderlike werk gange met 'n relatief soortgelyke bome in terme van individuele boom volume en vorm. Die spesie bestudeer was 'n Eucalyptus grandis x camaldulensis kloon. Deurlopende helling data, in teenstelling met helling kategorieë, vir elke posisie waarteen die stropers self sal posisioneer om die oes en verwerking onderneem, is afgelei met behulp van groot voetspoor LiDAR data van die gebied. Die doel gebou stroper is nivellering aktief, want in teenstelling met die Volvo wat nie was. Afgesien van verskille in massa, is die Volvo nie aangepas is vir bosbou werk en die valbome was op verskillende kante van die spesifieke masjien. Kosteberekeninge is uit op elke masjien om te bepaal watter masjien meer kostedoeltreffend was gedra. Die studie ontwerp was 'n 2 x 2 faktoriale ontwerp met twee behandelings (tipe masjien) teen helling en individuele volume boom as faktore.

Die resultate dui daarop dat die produktiwiteit van die graaf gebaseer masjien het met 0.048m3.PMH-1 vir elke 1% -verhoging in helling. Die doel gebou masjien is nie beduidend beïnvloed deur helling in hierdie studie en 'n gemiddelde produktiwiteit ongeag uiterste helling gehandhaaf. Die voorgeneem gebou masjien is gevind dat 'n hoër gemiddelde produktiwiteit het (16.24 $m^3.PMH^{-1}$) as die graaf gebaseer masjien (13.00 $m^3.PMH^{-1}$), maar dit ekstra produktiwiteit het teen 'n prys, as die graaf gebaseer masjien meer was ekonomiese per kubieke meter. Die gemiddelde koste oes vir die doel gebou masjien gevind om R122.67.$m^{-3}$ wees terwyl die graaf gebaseer masjien 'n gemiddelde koste van R94.46.$m^{-3}$ behaal.

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# 1. Introduction

Industrial plantation forestry is relatively small in terms of total land use in South Africa, with only 1% or 1.27 million ha (DAFF, 2015) being attributed to this land use (FSA 2013). Despite this the South African forest industry is highly regarded in terms of plantation forestry management worldwide (Eggers, McEwan, & Conradie, 2010). The pulp and paper industry consumes approximately 66% of all fibre supplied by the commercial forest industry in South Africa (FSA 2013). In order to satisfy this demand, various fast growing hardwood *Eucalyptus* species are relied on to supply approximately 84% of the raw material used in pulp and paper manufacturing in South Africa (FES 2011; van der Merwe et al., 2014).

Mechanised cut-to-length (CTL) harvesting systems are becoming more evident in the South Africa as opposed to more labour intensive systems of the more recent past, such as motor-manual or semi-mechanised systems, which are being systematically phased out (van der Merwe et al., 2014). This is largely due to the benefits of improved operational safety, improved product quality and potentially higher rates of production associated with mechanization (Hogg et al. 2011).

However the emergence of excavator based harvesters as potentially suitable alternatives to purpose built machines has opened a debate as to which is the most suitable machine to use in terms of cost and productivity within the South African forestry environment and context. The number of excavator based machines in use in South Africa, and worldwide for that matter, attests to their suitability in easy terrain, where levelling technology is not required. However in steeper terrain the outcomes are not that clear.

Slope is an important factor to consider in timber harvesting, especially when using mechanized harvesting systems (Strandgard et al. 2014). Different machines have different traction capabilities which, at the extremes, pose a challenge or benefit in terms of equipment selection. Purpose built machines (PBM) with levelling capability and tracks are able to work in slopes of up to 60%, but are generally restricted to less extreme slopes in practice (Ramantswana et al. 2012). Excavator based machines (EBM) are typically restricted to more gentle slopes of up to 45%. There is currently limited literature in a South African context, which looks at determining the effects that steep terrain has on the productivity of either of the machine types used in this study.

In this study two harvesters were compared. A TimberPro TL-725B self-levelling, purpose built machine (PBM) and a Volvo EC-210BF excavator based machine (EBM). Both machines were equipped with Maskiner SP-591-LX single-grip harvester head for felling and processing (including de-limbing, de-barking and cross-cutting) of *Eucalyptus grandis x camaldulensis*. Both machines were used to fell and process hardwood *Eucalyptus* trees into 5.5 metre assortments, which were then stacked for extraction by forwarder. In this study processing includes de-barking, de-branching and cross-cutting.

Timber harvesting is a high cost activity in the wood procurement value chain. Up to 40% of the total value-chain cost can be attributed to harvesting and extraction (Spinelli et al., 2002). In South African mechanised CTL harvesting operations EBMs are the most commonly used machines with PBMs relatively rare in comparison. As PBMs are considerably more expensive in terms of purchase price and running costs than EBMs, it is important for contractors and forest owners in the industry to understand the productivity and relative cost differences between the two machines under similar operating conditions.

The objective of this study is to determine the effect of slope on the cost and productivity of a purpose built levelling and an excavator based single-grip harvesting machine in order to aid in system selection decisions.

# 2. Literature review

## 2.1. South African pulp-wood harvesting

The South African pulp and paper industry forms the major portion of the South African forestry industry, with the two biggest names, Mondi and Sappi, having become global players (FSA 2013) and spearheading the drive towards mechanisation in South Africa. Mechanization of harvesting operations in the pulp and paper industry began with the introduction of tractor trailers for extracting logs to roadside after being felled by chainsaw operators (van der Merwe et al., 2014). Single-grip harvesters have been used in the past but only became more prominent as harvesting heads were developed to effectively process trees into log assortments, particularly with regard to debarking of eucalyptus for pulp wood. This advancement allowed harvesting systems to completely remove chainsaw operators from the operations which in turn improved safety, wood quality and productivity (Alam et al, 2012, van der Merwe et al., 2014).

Fast growing Eucalypt species are common in the South African pulp and paper industry as they provide good quality pulping material combined with relatively short rotation periods (FSA 2013). There are currently many Eucalypt sub-species available for commercial forestry and most of the big companies in South Africa have their own breeding programs to try and attain a competitive advantage in pulp yields. The majority of tree species grown in the South African pulp and paper industry are harvested between 8 – 12 years of age. Due to this short rotation age the mean Diameter at Breast Height (DBH), and hence mean volume, of trees grown for pulp and paper production is less than that of saw-timber (SAGBHH, 2010).

### 2.1.1. Mechanised ground-based harvesting

Fully mechanised ground-based harvesting operations have been common in the northern hemisphere since the early 1980’s (Macdonald & Clow., 2003). Prior to this harvesting often consisted of semi-mechanised systems with skidders and rudimentary forwarders being used in some countries since the 1960’s (Macdonald & Clow., 2003).

As opposed to the rapid adoption of mechanised timber harvesting in Europe and elsewhere, in South Africa the transition has been more gradual, with fully mechanised systems only becoming more common over the last decade. In the saw timber industry mechanisation progressed from animal extraction to crawler tractor based systems and eventually articulated ground based skidders as part of tree-length (TL) systems in the early 1980’s (Macdonald & Clow., 2003). During the 1990’s feller-bunchers were introduced to work with grapple skidders in pine saw timber operations (FSA 2013). These machines along with chainsaw operators were often used in full-tree (FT) harvesting systems as well as TL systems.

In South Africa pine and eucalyptus pulpwood operations have traditionally been motor-manual, with debarking, stacking and loading activities being manually orientated. Although these manual and motor-manual systems still exist today, for ergonomic, safety and productivity related reasons, they are less used in favour of mechanised options (van de Merwe et al., 2014).

The most commonly used harvester types in mechanized CTL harvesting systems in South Africa are excavator based machines (EBM), except in areas that restrict their use due to ground roughness and/or steep slopes in which case a purpose built levelling machine (PBM) may be used (Hogg et al., 2011, Ramantswana et al., 2012). An EBM is cheaper to purchase and operate than a PBM, despite the fact that the EBM's need to be modified in order to operate in a forest environment (Berkett, 2012). They also have a good resale value once they reach the end of their useful (forestry) life as opposed to PBM's which are largely obsolete both structurally and technologically at life end.

Terrain is the major deciding factor for harvesting system selection, with slope being the most influential terrain attribute (MacDonald, 1999). Ground roughness also influences machine and system selection (McEwan et al., 2013) and will specifically influence the choice of carrier in a harvesting system, i.e. tracked versus wheeled machines. Tracked machines are not able to easily negotiate terrain containing many obstacles (SAGBHH, 2010). Wheeled machines are also affected by rough terrain but not to the same degree as tracked machines (SAGBHH, 2010). Figure 1 represents an example of a machine selection decision support diagram.

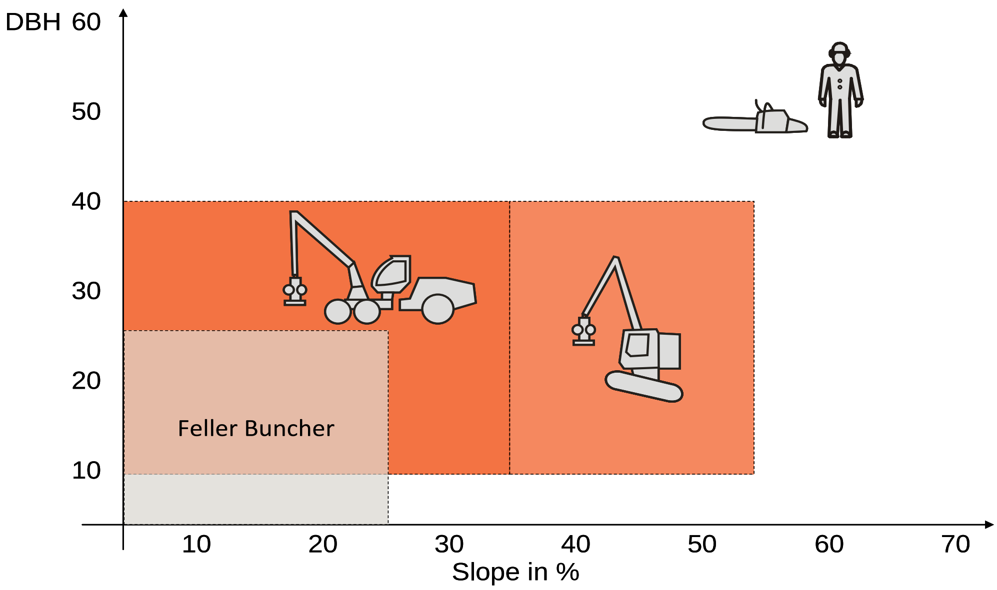


**Figure 1: Harvesting machine selection example based on slope and tree size (SAGBHH, 2010)**

Mechanized harvesting has become an integral part of most South African forestry operations over the last decade (FSA, 2013, van der Merwe et al., 2014). The challenges with the work force in

South Africa are a contributing factor to the increased prevalence of mechanized harvesting operations. HIV/AIDS and various socio-economic issues associated with rural areas in the country, where forestry is generally practiced, have limited the number of skilled labour available to the industry (Shackleton et al., 2007; Pogue, 2008).

### 2.2. Harvester productivity and costs

There have been a number of international studies aimed at predicting productivity and cost implications in mechanised harvesting systems; however the majority of the literature is not specifically related to South African conditions. Existing research reports indicate that productivity is affected by a variety of factors such as operator experience and motivation, work objective, tree form and volume, slope, terrain conditions, shift timing and maintenance practices (Ackerman et al., 2014; Alam et al. 2012; Ghaffariyan et al. 2012; Ramantswana et al. 2012; Ramantswana et al. 2013; Spinelli et al. 2002a; Spinelli & Magagnotti 2010; Spinelli & Magagnotti 2013; Williams & Ackerman 2016) . All these studies found tree size (DBH and tree volume) to be the most influential variable in terms of machine productivity. This is due to the difference in time taken to harvest and process trees of different volumes not being directly proportional to the difference in volume, meaning bigger trees will lead to higher productivity (Ramantswana et al. 2012). But this trend does not continue indefinitely and is subject to diminishing returns as tree size becomes excessively larger than the harvester head is designed to handle (Stankiç & Porsinsky 2012). In a study based on large follow up data sets of CTL harvesters in Sweden, Eriksson & Lindroos (2014) developed models to predict harvester productivity of a variety of machines of different sizes based on a number of variables. Productivity and costs are highly correlated, with costs decreasing as productivity increases. Hence harvesting costs per unit of production decrease as tree sizes increase (Puttock et al, 2005) (Figure 2).

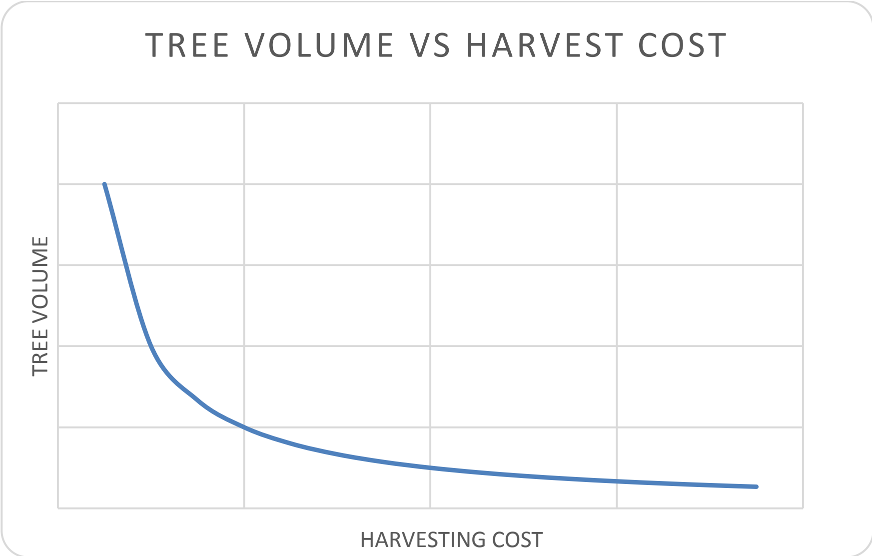


**Figure 2: Relationship between tree volume and harvesting cost (adapted from Puttock et al,. 2005).**

### 2.2.1. Operator influence

Operator performance and experience is recognised as significantly influential in achieving the maximum potential of the machine (Hogg et al., 2011., Purfürst & Erler, 2011). Aside from tree size, the next most significant source of variation, influencing harvester productivity is the performance of the machine operator itself (Strandgard et al., 2016). A machine has intrinsic capabilities and limits. These limits can only be reached if the machine is being operated by a competent operator. Equally experienced operators will often have very different outputs depending on a variety of personal and career related traits (Purfürst & Erler, 2011). The machine operator can have a significant impact on the costs, productivity and utilisation of the machine (Hogg et al., 2011). Productivity and cost rates can vary by more than 40% between equally experienced operators (Hogg et al., 2011, Strandgard et al., 2014). Operator performance is influenced by factors such as experience, training, job satisfaction, financial incentives and machine ergonomics (Hogg et al., 2011).

## 2.3. Slope

Slope plays an important role in mechanized forest harvesting systems selection (Acuna et al., 2011., Ghaffariyan et al., 2012., Strandgard et al., 2014). Slopes in excess of 60% promote alternative methods of harvesting and extraction, such as tethered machine harvesting, cable-yarding and helicopter extraction, but these methods are generally more costly, less efficient and achieve lower rates of production (Ramantswana et al., 2013).

### 2.3.1. Slope classification

Slopes can be described in percent (%) or degrees (°). Percent slope, which is the preferred method in forest operations research (Pulkki & Manyuchi 2002), is an indication of the ratio between the change of position in the vertical direction (rise) and the horizontal direction (run) caused by a slope.

The majority of the studies having been reviewed use percent slope and slope classes to define the extent of the slope experienced by the machine (Alam et al. 2012; Ghaffariyan et al. 2012; Brown et al. 2013; Strandgard et al. 2014). Slope classes are created by breaking the slope extent up into a number of intervals and describing theses intervals from flat to steep (Alam et al. 2014). However, looking at slope as a continuous variable allows for more precise estimation of the influence of small fluctuations in slope as opposed to only between a predetermined set of slope classes. Each percent of slope is essentially a slope class with the total number of classes being defined by the extent of the slopes encountered on the site (Strandgard et al. 2014).

#### 2.3.1.1. Light Detection and Ranging (LiDAR)

There are currently two commercial remote sensing systems extensively being used in forestry resource management research to derive ground elevations and slope (Akay et al., 2009). Namely, Light Detection and Ranging (LiDAR) and Inter-Ferometric Synthetic Aperture Radar (IFSAR). LiDAR has been extensively utilised in various applications where as IFSAR is usually used for large landscape level studies (Reutebuch et al., 2005).

LiDAR uses remote-sensing technology to analyse the landscape similarly to the way in which radar works. LiDAR utilises laser reflection and point mapping to analyse the environment from a 3-dimensional perspective (Hohenthal et al. 2011; Lin et al. 2011; Lin & Hyyppa 2012; Brown et al. 2013). LiDAR data can be collected from the ground, terrestrial LiDAR, or from the air, airborne LiDAR. Terrestrial LiDAR data has enables researchers to precisely analyse the forest from below the canopy, allowing for improved enumeration data through non-destructive methods (Lin et al. 2011; Lin & Hyyppa 2012). However this can be very time consuming as the scanner needs to be manually moved numerous times. Airborne LiDAR data allows researchers the opportunity to develop an extremely accurate three-dimensional map of the landscape it is flying over (Akay et al., 2009). Airborne LiDAR systems are generally classified as small-footprint or large-footprint systems and can be carried by a fixed-wing drone, a rotor powered drone or conventional aircraft. Fixed-wing drones are favoured in the forestry industry as these units fly faster, are more stable and have a greater range than rotor drones (Tang and Shao, 2015).Studies in the past have used LiDAR data to estimate slope when trying to deduce a relationship between slope and productivity of harvesters or processors (Lin et al. 2011; Strandgard et al. 2014). The LiDAR data may also be used to determine the different slope ranges which can assist in the pre-trial layout of the swaths to be harvested during a time-study (Hyyppä et al. 2008). The airborne LiDAR device fires a barrage of laser beams down to the forested landscape below. The laser beam is then intercepted by the trees and the ground surface. Some of the laser beam is reflected back to the LiDAR device. The time taken for the beams to be reflected back to the device is used to estimate the distance from the device to the point of reflection. The highest points, the tops of the trees, are the first reflections to return to the device. Thus the final reflections to reach the device are from the lowest points, i.e. the ground surface (Figure 3). Once all of the data has been collected, software is used to create accurate 3D maps and images of the ground surface which can be used to analyse the area through GIS software (Hilker et al., 2012).

The most commonly used LiDAR derived images in forestry are known as digital elevation models (DEM) and digital terrain models (DTM's). DEM's provide information relating to the elevation of the landscape and accompanying features (Akay et al., 2009). Before LiDAR and other DEM or DTM producing technology became available, researchers would need to use a clinometer and physically measure the slope for every required data point or utilise a minimum sample across the site and then extrapolate the results over the entire compartment (Brown et al., 2013). This is a very time consuming activity and causes major disturbances in terms of the machines work flow being interrupted constantly (Ghaffariyan et al. 2012).

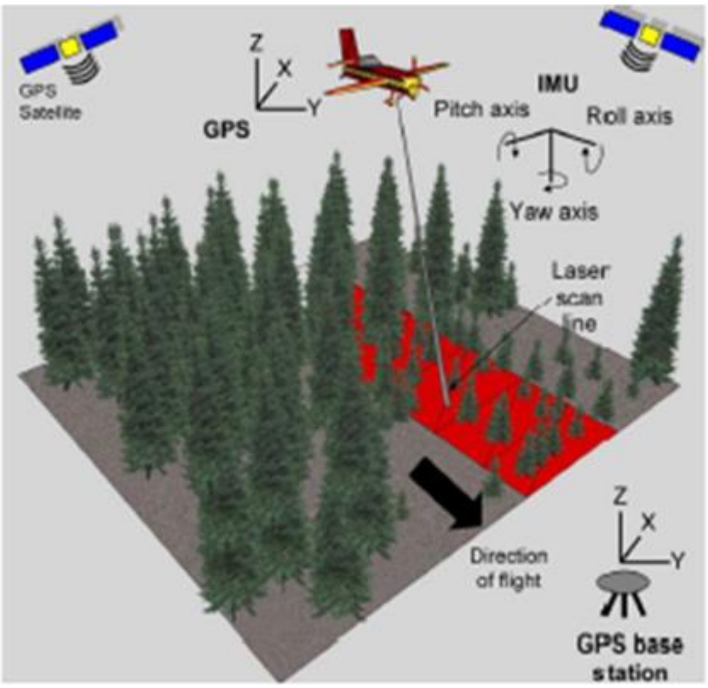


Figure 3: LiDAR in forestry (Mondi ltd)

### 2.3.2. Effect on terrain due to harvesting on steep slopes

Another important factor to consider when harvesting in steep terrain is the impact of the operation on the soil itself (Strandgard et al. 2014). Heavy machines can cause damage in terms of compaction and erosion in steep terrain (SAGBHH, 2010). This risk can be mitigated by ensuring appropriate tracks are installed on the machines and that the operators are properly utilising the excess brush and branches as a ground cover for the machines to drive on top of (Wood et al. 2003). The South African National Terrain Classification system (SAGBHH, 2010) has defined ground roughness based on the presence, extent and concentration of rocks and depressions affecting the terrain. Rough terrain combined with steep slopes and shallow or loose topsoil are also seen as a safety hazard as the machines can slip or topple and also cause erosion damage (McEwan et al., 2013). These factors have led to the slope safety limits imposed on machines operating in South Africa's forestry industry (FSA 2013).

### 2.3.3. Machine selection in steep terrain

Different machines and harvesting systems have different slope limitations (McEwan et al., 2013). The terrain limits on ground-based harvesting depend on what kind of machines are involved and are largely dictated by environmental sensitivity as well as safety concerns (FSA 2013, van der Merwe et al., 2014). In practice the limits are ultimately decided on by the entity responsible for managing the operation. Ground-based mechanized harvesting is generally limited to slopes of 60% when utilising a machine that has levelling capabilities (SABGHH, 2010). Wheeled and tracked non-levelling machines are generally restricted to working on slopes that do not exceed 35% and 40% respectively (SAGBHH, 2010). Modern PBM's often have some form of levelling technology, which allows them to work safely on steeper slopes than non-levelling machines (Strandgard et al., 2014). Wheeled and tracked levelling machines are restricted to slopes not exceeding 45% and 60% respectively. This is with respect to the machines working up or down a slope, perpendicular to contours, as opposed to across a slope. Side slope limits are generally lower (10%-15%) (Berkett, 2012).

### 2.3.4. Comparing EBM and PBM

EBMs have made an entrance to the forest operations, essentially replacing PBM in certain operations. They are firstly less expensive to purchase and have significant resale values at life end in a forest operation context. On the other hand used construction type machines can be purchased for forestry work. They however have terrain limitations. Non-levelling, unassisted EBMs should not work on slopes of over 45% for safety reasons. Exceeding 45% slope leads to machine instability and often causes a reduction in performance/productivity (Garland, 1997). Non-levelling EBMs characteristically have an extended counterweight behind the operator to balance the machine when carrying a load with the boom. On steep slopes this counter weight causes the machine to become unstable as the centre of gravity moves when the cabin swings (McEwan et al., 2010). The standard hydraulic systems on EBMs are also essentially not adequate for forestry purposes and generally mean the hydraulic system is working at its maximum all the time which can lead to high maintenance costs and breakdowns (SAGBHH, 2010). The counterweight may also lead to excess strain on the hydraulics of the machine on steep slopes as more force is required to overcome the gravitational forces on the counterweight. When the machine is on a flat surface rotation of the cabin is not affected by gravity, but when the machine tilts, as on a slope, the rotation is also influenced by the earth's gravitational pull (SAGBHH, 2010).

The development of the levelling machine cabin has allowed machines to harvest on ever steeper slopes. The levelling ability of the machine, combined with a more compact cabin design when compared with excavator based machines, allows a favourable centre of gravity to be maintained even as the cabin swings (McEwan et al., 2010). Some tracked self-levelling harvesting machines can perform well on slopes of up to 60%, provided that the under-foot conditions are good (Stampfer and Steinmuller, 2001). One of the major advantages of PBMs in CTL harvesting is that the hydraulics systems in these machines are generally better suited to handle the pressures needed to operate the machine as well as the harvester head (SAGBHH, 2010). The under carriage of a PBM is characterised by a high ground clearance which is not standard on an EBM but is an important feature for forestry machines (SAGBHH, 2010). PBMs are generally equipped with Operator Protection Systems (OPS), Fall On Protection Systems (FOPS) and Roll Over Protection Systems (ROPS) by the manufacturer and hence require no further modifications to meet the safety requirements to operate in a forest environment, whereas EBMs often require these features to be installed after purchasing the machine (SAGBHH, 2010).

### 2.3.5. Effect of slope on harvester productivity

A number of studies have looked at the influence of slope on harvester productivity, with a range of different results. Unfortunately few studies were found that looked at the machine types chosen for this study. Two studies that looked at the effects of slope on productivity of feller-bunchers were FPInnovations (2008) and Brown et al., (2013). Brown et al. (2013) found a reduction in productivity of 24% in steep slopes 33% - 51%, when compared to moderate slopes 19% - 33%. The slopes in the Brown et al., (2013) were derived from LiDAR data. A study by FPInnovations (2008) found a reduction in productivity of 30% between 10% - 19% slope and 19% – 33% slope based on modelled results from a number of different feller-buncher productivity studies.

Strandgard et al. (2014) found that slope had no significant effect on the productivity of a single-grip processor. They also suggested that the larger mean tree size in their study may have led to a significant difference in the productivity of the machine in different slope classes. The mean tree volume encountered in the Strandgard (2014) study averaged close to 0.5m$^3$ per tree. It is important to note that the machine being analysed in the study was not used to fell the trees, only to process the trees into log stacks. The trees were harvested by a feller-buncher prior to the study. Having the trees pre-felled by a feller-buncher means that the processor does not have to move as much as a single-grip harvester would have to and hence did not have to deal with slope changes and obstacles in the same way. This is important as the processor operator was able to manoeuvre the machine into a comfortable operating position from which to work, and this may have contributed to the consistent productivity rates achieved throughout the study. Strandgard et al. (2014) also stated that the majority of the trees studied in the steeper slope class were from the lower end of the slope range and this may have contributed to the lack of significant difference in productivity between the classes. The contradictory results of previous studies highlight the lack of understanding in the research community as to the true effects of slope on harvester productivity.

### 2.4. Time study

Time study is a method of determining how much time is required for an activity under specific conditions (Wang et al, 2004). Time study is a tool in operations research that allows researchers to isolate and measure specific parts, referred to as elements, of an activity (Nakagawa et al., 2014). Applied operational research can help improve forest operations and give benchmarks to guide decision making (Acuna et al. 2011). Time study which identifies strong relationships between variables can be used to deduce functions which allow the performance of a system to be assessed with relative ease (Eggers et al. 2010). In timber harvesting for instance, a time-study can produce a function to predict productivity based on the size of the trees as an input variable. This means the productivity of a machine can be assessed by simply having the function, the mean tree size and a clock to time the machine (Acuna et al. 2sa011). Work time standards in South Africa forestry were first introduced by the Department of Forestry Organisation and Method Study team which produced time standards to be expected from various plantation activities (Crickmay et al., 2004).

The concept of time study is relatively simplistic which allows it to be easily adapted to a variety of different activities. All harvesting activities have a number of smaller processes which need to be completed in order for the activity to be completed (Ghaffariyan et al. 2012). These smaller processes are referred to as elements in the time study. Some elements, such as delays, are not necessary for the activity to be completed, yet they do occur and need to be measured in order to capture the most accurate representation of the actual rate of work (Nakagawa et al. 2014). Thus it is important to ensure that all possible elements are identified and defined appropriately. This enables element related inefficiencies to be identified and better understood, leading to improvements in overall operational efficiency (Ghaffariyan et al. 2012). Acuna et al. (2012) developed a set of guiding principles for conducting a time study of harvesting with the help of a handheld computer. These principles have been widely accepted by researchers and professionals in the field (Spinelli & Magagnotti 2013).

### 2.4.1. CTL harvester time study

Time studies carried out on harvesting machines which form part of a CTL system have typically used the elements described by Acuna et al. (2012). Utilising standardised elements allows for comparison of different studies regardless of the location or stand characteristics. The Department of Forestry and Wood Sciences at the University of Stellenbosch in co-operation with a number of industry bodies has developed a South African standard for forest harvesting time-study elements (Table 1) (Ackerman et al., 2014).

**Table 1: Machine elements for CTL harvester time-study**

| Time element | Description |
|---|---|
| Boom-out | Starts when the operator begins moving the harvester head to a tree, ends when the harvester head has secured the tree for felling. |
| Fell | Starts when the harvester head begins felling the tree with the attached chainsaw, ends when the tree is felled. |
| Boom-in | Starts when the tree is felled, ends when the tree begins moving through the harvester head for processing. |
| Process | Starts when the tree begins to move through the head, ends when the head has released the last piece of the tree. |
| Move | Starts when the tracks begin moving, ends when the tracks come to a stop. |
| Delay | Starts when the machine unexpectedly stops working, ends when work begins again. |

### 2.4.2. Time study tools

There are a number of different tools available for conducting a time study. The most basic scenario would include stop watches, pens, paper and a clipboard (Eggers et al. 2010). Nowadays researchers have more options to choose from, such as hand-held computers, specialised time study software and lightweight portable video cameras. The most advanced software will be programmed to automatically identify different elements from video recordings, meaning there is little human involvement in the data capturing process which allows for less human error and effort (Strandgard et al. 2014).

A handheld computer is ideal for time study data collection, especially when studying activities that have many elements with relatively short cycle times (Eggers et al. 2010). Nowadays even a smart phone could be used to conduct a time study. Battery life, processing speed, GPS capability and ergonomic design are the most important factors to consider when choosing a device. The software and user proficiency generally dictate the quality of the data collected in a time-study.

GPS is a useful tool in forest research as forestry operations generally cover vast areas and pin-pointing exact locations is very difficult without a GPS unit. This is especially important when conducting a study which uses LiDAR data as GPS enables researchers to precisely locate areas of interest and then overlay the LiDAR images (Tang and Shao, 2015). Without the GPS in the field to precisely locate the machine, the LiDAR data has little value to machine-slope interaction studies.

All time-study software is designed to assist researchers in capturing important time sensitive data from a variety of different activities. Researchers need to be able to describe any number of elements with individual behaviours, define start and stop points of work cycles and access some live basic statistical summaries whilst in the process of conducting a study (Nakagawa et al. 2014). Most software can be installed on a handheld computer and the department of Forestry and Wood Science at the University of Stellenbosch has developed a time-study application which can be installed on an android device (www.forestproductivity.co.za). Time-study software must contain a precise clock and allow the researcher to easily upload the time-study data into a spreadsheet for further analysis. Specialised statistical software is needed for post-processing to analyse the data and develop prediction models based on the results of the time-study.

### 2.5. Literary summary

This literature review has shown that although there is a significant amount of research regarding the different aspects of this study's core focus, there is no literature which looks at these aspects together. This is most notable with regards to the effects of slope on the productivity of single-grip EBM and PBM harvesters, looking at slope as a continuous variable and the comparison of an EBM and a PBM. The majority of the literature regarding the effect of slope either looks at different machine types, different systems or combinations of both.

# 3. Methodology

## 3.1. Study site

The study area was located approximately 8 km east of Melmoth in the KwaZulu-Natal region of South Africa (Figure 4). The estate in which the study site is located is managed by Mondi and was planted to *Eucalyptus grandis x camaldulensis* for pulp and paper production. Harvesting occurred in late July 2014 during the winter period which is the dry season in that area. The trees were 8 years old at the time of felling (Table 2). This compartment was selected due to varying degree of slopes from level to 55% which could be easily accessed with minimal machine relocation.


Figure 4: Melmoth geo-location

### 3.1.1. Site and stand characteristics

The area is situated in the summer rainfall area of South Africa and receives approximately 875mm of precipitation a year, most of which falls between October and March (Figure 5). The site is approximately 740m above sea level (680m to 820m). The soil in the study area was red and yellow apedal, well drained clayey soil with a low base status (Mondi ltd). Figure 5 shows the climatic chart, temperature and rainfall over a 12 months period, for the study area.

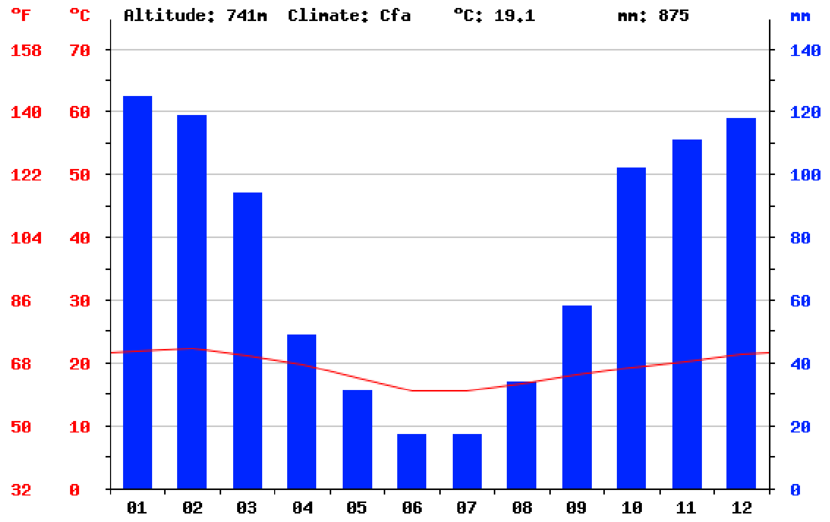


Figure 5: Climatic chartreference for data

Table 2 summarises relevant site and stand information for the study site and stand characteristics.

Table 2: Site and stand characteristics based on cruise and experimental data

| Attribute | Description |
|---|---|
| Species | *Eucalyptus grandis x camaldulensis* |
| Stand age at felling (y) | 8 |
| Stocking (Stems.ha$^{-1}$) | 1667 |
| Mean slope, (%)(Range) | 23 (5 – 55) |
| Mean DBHOB, (cm). (Range) | 15.89 (9 – 27.2) |
| Mean height, (m). (Range) | 19.6 (15.1 - 24.2) |
| Mean merchantable tree volume, m$^3$. (Range) | 0.154 (0.034 – 0.477) |

Terrain was classified according to the South African National Terrain Classification System for Forestry (Table 3); (SAGBHH, 2010). This system classifies slope into seven different classes from “Level” to “Very steep”. Ground conditions refer to the soil itself and its load bearing capacity in dry, moist and wet conditions. Ground conditions are determined by the soil type, clay content and soil moisture. Ground conditions are divided into five classes ranging from “Very good” to “Very poor”. A soil with high load bearing capacity will be able to support higher pressures from the wheels or tracks of machines. Soils with a low load bearing capacity will be eroded by machines that are sinking into the ground if the machines do not have enough flotation (McEwan et al., 2013). Ground roughness refers to the profile of the landscape, i.e. depressions, mounds, rocks etc., and is classified into five different classes ranging from “Smooth” to “Very rough” (SAGBHH, 2010).

Table 3: South African National Terrain Classification classes (SAGBHH, 2010)

| Ground conditions | Ground roughness | Slope (%) |
|---|---|---|
| 1: Very good | 1: Smooth | 1: 0 to10 = Level |
| 2: Good | 2: Slightly uneven | 2: 11 to 20 = Gentle |
| 3: Moderate | 3: Uneven | 3: 21 to 30 = Moderate |
| 4: Poor | 4: Rough | 4: 31 to 35 = Steep 1 |
| 5: Very poor | 5: Very rough | 5: 36 to 40 = Steep 2 |
| | | 6: 41 to 50 = Steep 3 |
| | | 7: >50 = Very steep |

The compartment harvested in this study is classified in Table 4 according to the National Terrain Classification system. The National Terrain Classification System was developed by Erasmus, 1994 and can be found in the South African Ground Based Harvesting Handbook (SAGBHH, 2010).

Table 4: Terrain classification of study site (SAGBHH, 2010)

| Attribute | Value | Designation |
|---|---|---|
| Slope range | (1) through (6) | (Level ) through (Steep 3) |
| Ground conditions | (2)/(3) | (Good)/(Moderate) |
| Ground roughness | (3) | (Uneven) |

## 3.2. Research design

This study is conducted as a simple 2 x 2 factorial design. Table 5 describes the different treatments along with the slope and volume factors.

Table 5: Research design

| Factors | Treatments | |
|---|---|---|
| | Purpose built machine<br>Treatment 1 | Excavator based machine<br>Treatment 2 |
| Slope<br>Factor (A) | 1A | 2A |
| Volume<br>Factor (B) | 1B | 2B |

PBM (treatment 1) and EBM (treatment 2) (Figures 7 and 8) are applied to the compartment over the range of slopes (factor A) and tree volumes (factor B). Ground slope and tree volume are both numerically continuous variables meaning they do not have a set number of applications at each level. The slope changes at any point and any one slope percentage may not necessarily appear again. Due to the lack of controllability this type of variable is seen as continuous in this study as opposed to grouping into classes as in previous studies. Thus the analysis utilises the exact measured slope value at each point of interest instead of the class it falls into. It is probable that the machine will be exposed to the entire range of slopes through application of the harvesters on the designed five-tree wide harvesting corridor that crosses the range of available slopes.

### 3.2.1. Harvesting method

The harvesting method for this study matched the typical operational approach used by the harvesting contractor at the time of harvesting. The harvesters fell and process (delimb, debark and cross-cut) five-tree wide corridors through the compartment. The processed log lengths are placed into stacks to the right of the machine as it moves through the corridor. Once it reaches the end of the corridor it must turn and harvest the adjacent corridor in the opposite direction. This allows the logs produced from both five-tree wide corridors to be placed onto the same log stacks, represented by the red line in Figure 6.

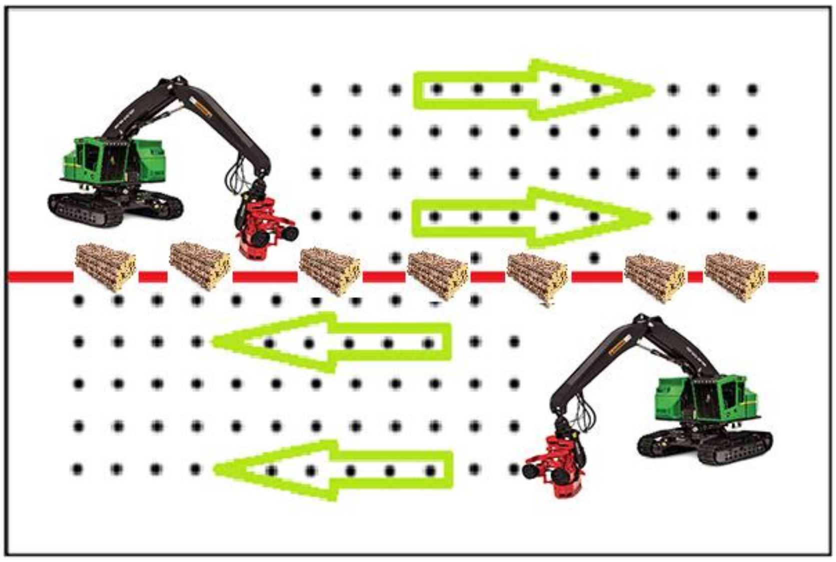

Figure 6: Five tree wide corridors with logs stacked between the corridors

### 3.2.2. Machine description

Both EBM and PBM machines used the same single grip Maskiner SP-591LX harvester head. This harvester head is used to fell, debark, de-branch and cross-cut the trees before placing them into log stacks making them available for subsequent forwarding to roadside landing. Notable differences between the two machines include the cab levelling ability of the PBM, the boom being positioned on right of the operator in the PBM as opposed to the left of the operator in the EBM, and the tracks on the PBM having deeper and more aggressive grouser plates which aid with traction on steeper slopes (forest operation specific). The PBM also has a higher ground clearance as opposed to the EBM which is not designed specifically for forestry applications and has smaller and less aggressive grouser plates. The more aggressive nature of the PBM's tracks, combined with the levelling ability, allows more stability on slopes and hence the ability to safely work on steeper slopes than the EBM. The PBM is 2000 kg's heavier, with a higher kW rating than the EBM (Table 6) and is able to distribute its weight better due to the levelling capability and tracks.


Figure 7: Volvo EC-210BF (Martin 2015)

Figure 8: TimberPro TL-725B (Martin 2015)

Table 6: Machine specifications

| Variable | Volvo EC-210-BF (EBM) | TimberPro TL-725B (PBM) |
|---|---|---|
| Operating weight (with attachments), (kg) | 24 000 | 26 000 |
| Boom reach, (m) | 9.4 | 7.9 |
| Fuel capacity, (l) | 350 | 378 |
| Cab rotation, (degrees) | $360^o$ | $360^o$ |
| Levelling cabin | No | Yes |
| Engine capacity, (l) | 5.1 | 8.3 |
| Power, (kW) | 155 | 280 |
| Fuel consumption, (l/PMH) | 23 | 35 |

### 3.2.3. Operator influence

This study utilised a single operator experienced in the operation of both the EBM and PBM. The reason for this is that it is assumed that there will be minimal variation in this operator's performance between the two machines as opposed to the variation between two different operators, which can be highly variable according to the literature (Hogg et al. 2011). The operator is assumed to be competent with 10 years of experience in mechanised CTL harvesting operations for the current contractor. Operation of both machines is essentially the same but for the PBM's ability to adjust the angle of the cab relative to the tracks in the vertical direction. The other difference that may be significant is the fact that the boom is situated to the right of the operator in the PBM and to the left of the operator in the EBM. No literature could be sourced on studies which indicate that this configuration might have an effect on the performance of the operator.

### 3.2.4. Data collection

#### 3.2.4.1. Sample size determination

Due to the continuous nature of the variables being measured it was determined that a minimum sample size of 60 trees per machine would be sufficient for statistical analysis. In order to achieve robust statistical inferences in this study a sample size of 500 trees per machine was used. The initial 500 trees per machine were reduced by outliers and recording errors during the time study. This resulted in each machine processing ~ 400 trees to be used in the study.

#### 3.2.4.2. Single tree dimensions

Diameter at breast height, measured over bark (DBHOB), of the study trees was recorded using a diameter tape with an accuracy of 0.1 cm. The DBHOB was measured on every tree utilised in the study. Whilst measuring DBHOB, each tree is allocated a unique number in order to identifying the tree during harvesting. The heights of 100 representative trees, chosen from various locations on the site and spanning across the range of DBHOB available, were measured using a Haglof Vertex laser hypsometer with an accuracy of 0.1 m. The heights and DBHOB of these representative trees were used to derive a regression which allows the heights of the remaining tress to be estimated based on the DBHOB measured for each tree (Bredenkamp 2000). Note that this study took place in a plantation environment which means all trees are the same age and originate from the same clone, meaning there should be less variation between trees than would be found in a natural forest environment.

#### 3.2.4.3. Tree identification

As mentioned all trees used in the study were identifiable through a unique identification number to facilitate the pairing of tree dimensions with felling and processing times in order to correctly estimate productivity. The numbering of the study trees for each machine is done in consecutive order from left to right in the identified felling corridor. Once the study trees had been identified, all the trees that made up the edges of each corridor, that is the first and last tree of each row, were marked by having their unique ID number spray painted onto the stem at an angle which allowed the number to be easily noted during the actual time study. This method was used to save time and reduce the amount of numbers visible to the time-study team at any one time to avoid confusion. Note that this method works optimally when the researcher is viewing the machine at a $45^0$ angle to the front-left of the machine (Figure 9). This angle improves depth perception for the researcher, in terms of which row is being harvested, whilst avoiding the high risk danger zones of the machine's felling action. This is important as it can be challenging to identify the tree being harvested when attempting to look through the trees which are yet to be harvested.

Figure 9: Tree identification in PBM harvesting corridor (Martin 2015)

#### 3.2.4.4. Trial layout

Continuous five trees wide (10 m) harvesting corridors were laid out across the spectrum of slopes available at the study site (Figure 10) for each machine. Figure 10 is a 1 m resolution digital elevation model (DEM) derived from the LiDAR data used in this study.

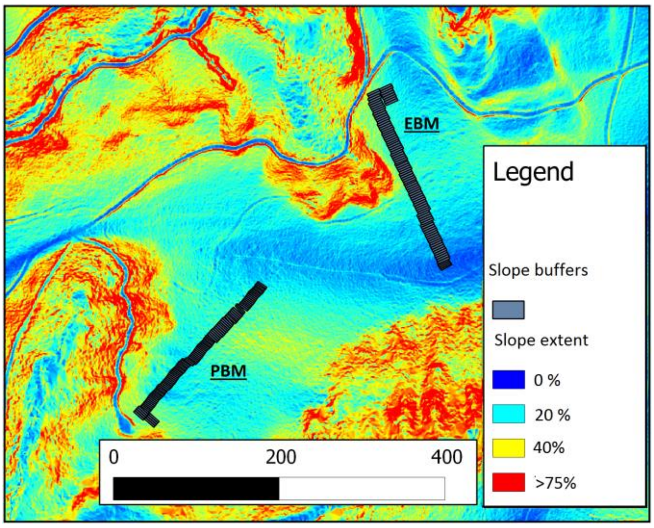


Figure 10: Machine Harvesting Corridors

The colouring of the map shows the extent of the slopes in a given area. While the area has slopes that range from flat (dark blue) to over 75% (red), the slopes within the study corridors ranged from flat to 45%.

#### 3.2.4.5. Time study

The time study was performed on both machines across the varying slopes and tree sizes available in each machines' allocated five trees wide demarcated harvesting corridor. The time study elements were chosen to align with the time study standards developed at the University of Stellenbosch (Williams and Ackerman 2016), with the exception that in this study, some of the elements were aggregated (Table 6) due to the nature of the study being focused on the total tree productivity versus individual element productivity. This aggregation was performed to make the collection of the time study data as efficient as possible. Time data were collected with a Trimble Geo-XM hand-held computer with Workstudy4+ software. The software was programmed to capture time in deci-minutes to allow for easier analysis as units divisible by 100, as opposed to 60, are more appropriate to relate to other numerical variables.

##### 3.2.4.5.1. Time study elements

As this study focuses on total tree productivity, not all of the machine elements needed to be individually measured. For instance, the elements "Boom-out", "Fell" and "Boom-in" were grouped and referred to as "Fell". Processing included delimbing, debarking and cross-cutting of the trees into 5.5m logs. This grouping resulted in four key elements: "Fell", "Process", "Move" and "Delays" (Table 7). Every completed set of elements is referred to as a cycle with the exception that the "Delays" and "Move" elements do not necessarily occur in each cycle. This means that each cycle, consisting of at least the Fell and Process elements, is the equivalent of one tree. The individual tree data is then paired with the corresponding cycle to calculate the productivity achieved for each tree harvested by each machine.

**Table 7: Machine elements for time-study**

| Time element | Description |
|---|---|
| Fell | Starts when the operator begins moving the head to a tree, ends when the butt end begins to move through the head. |
| Process | Starts when the butt end begins to move through the head, ends when the head has released the last piece of the tree. |
| Move | Starts when the tracks begin moving, ends when the tracks come to a stop. |

| | |
|---|---|
| Delay | Starts when the machine unexpectedly stops working, ends when work begins again. |

As the literature indicates that tree volume has the greatest influence on productivity, a key point in the field trials was ensuring that both harvesters were working with similar size trees across the range of slopes available in order to minimise variance associated with this factor. This was achieved by pre-sampling DBHOB in the areas intended for the study (Table 8) and then setting out the corridors appropriately.

**Table 8: Pre-sample DBHOB comparison**

| | Mean | Variance | Standard deviation |
|---|---|---|---|
| PBM | 15.57 | 5.93 | 2.43 |
| EBM | 15.44 | 6.13 | 2.48 |

## 3.3. Data analysis

Individual tree dimensions were recorded prior to harvesting. This data was then input to a spreadsheet. The harvester time study data captured with the Trimble handheld device during the time study was also output to a spreadsheet. Finally, the tree data and time-study data were then merged into a single dataset.

The data were then analysed using open source statistical software R (3.1.1) and R-commander (R Core Team, 2014). Statistical analysis includes developing generalised linear models and utilising analysis of variance and co-variance (ANOVA and ANCOVA) to analyse the influence of slope and volume on the productivity of both machines. This analysis does indicate if there is any significant difference (at 95% confidence levels) between the two machine types and if the slope has any significant effect on either machine with regards to their productivity.

### 3.3.1. Delay and movement time

This study aimed to compare the productivity of the machines only whilst they were actually working, hence all delay elements were excluded from the data set regardless of duration. This means that all productivity values calculated in this study refer to the work rate in terms of volume produced per productive machine hour ($m^3.PMH^{-1}$). Each of the “move” elements do not relate to one specific tree but are obviously crucial to the productivity of the machine as it needs to be able to move to a new position once it has harvested all the trees within reach. To bring this into account all “move” element times were summed together and divided equally between all of the trees harvested by each machine, allowing the additional time to be reflected in the productivity of every tree.

### 3.3.2. Volume calculation

A Schumacher and Hall (1933) type function was used to estimate merchantable tree volume (Equation 1).

$$ln(V) = b_0 + [(b_1) \times ln\{(DBH) + (f)\} + \{(b_2) \times ln(H)\} \qquad \text{(Equation 1)}$$

Where:

| | | | |
|---|---|---|---|
| V | = | Volume | ($m^3$) |
| $b_0$ | = | Parameter 0 | (-9.746) |
| $b_1$ | = | Parameter 1 | (1.715) |
| $b_2$ | = | Parameter 2 | (1.107) |
| f | = | Species factor | (-2) |
| DBH | = | Diameter at breast height under bark | (cm) |
| H | = | Merchantable height | (m) |
| ln | = | Natural logarithm | |

The above volume calculation requires that DBHOB be converted to diameter at breast height under bark (DBH). This was achieved through a simple conversion factor (Equation 2).

$$(DBH) = (c) \times (DBHOB) \qquad \text{(Equation 2)}$$

Where:

| | | | |
|---|---|---|---|
| DBH | = | Diameter at breast height under bark | (cm) |
| DBHOB | = | Diameter at breast height over bark | (cm) |
| c | = | Species conversion factor | |

### 3.3.3. Slope

The open source geographical information systems software QGIS (version: Lisboa) was used to analyse the terrain and determine the slope from large-footprint LiDAR data. Slope values for the study area were derived from Digital Elevation Models (DEM's) and Digital Terrain Models (DTM's) supplied by the company. These models were developed using LiDAR data gathered using an in-house fixed wing drone. The slope resolution was approximately 1 m and the validity of the data was verified by the company that supplied the data (Mondi Ltd).

This study considered slope to be a continuous variable and hence no slope classes were used during the data collection. This approach to slope is adopted due to the potential for a more precise understanding of the impact of small changes in slope as opposed to only noting the mean difference between predetermined cut off points, as is the case for slope classes. The slope at each point, where the harvesters were working from a stationary position, was estimated using the method developed by Strandgard et al. (2014). This involved creating a buffer (10 m X 3 m) around the point and then calculating the average slope from a minimum of six data point pairs within the buffer (Figure 11). The slope from each stationary position is then attributed to the productivity of each tree that is felled from that position. Note that the buffer size of 10 m x 3 m is not corrected for the slope in each buffer zone, meaning the true ground surface area of each buffer will differ depending on the slope in that area. Also note that the red buffer (Figure 11) is not a real life example but used to illustrate the concept and highlights that more than one tree will be harvested from each position and hence those trees will all have the same slope value.

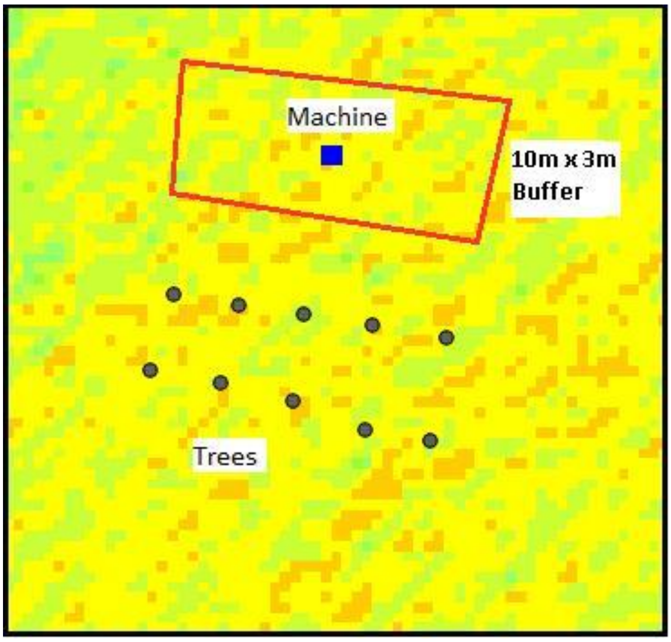


**Figure 11: Slope buffer design**

### 3.3.4. Linear Modelling

Generalised linear models were created for both machine types. The models describe productivity as a function of tree volume ($m^3$), and slope (%). Two models were developed from the collected data for each machine. The first model, Linear Model 1, was used to identify the main effects of both variables on the productivity of the machines. The second model, Linear Model 2 was used to test for covariance, and hence an interaction effect, between the ground slope and tree volume variables.

Both models were checked for validity of assumptions pertaining to the particular method of modelling.

#### 3.3.4.1. Linear Model 1 (LM1)

LM1 (productivity ~ volume + slope) predicts harvester productivity as a function of tree volume ($m^3$) and ground slope (%), it was subsequently tested through an ANOVA table to determine if the effect of either variable was significant. LM1 produces an equation for prediction of the form:

$$Productivity = (\beta_0)Volume + (\beta_1)Slope + (\beta_2) \qquad \text{(Equation 3)}$$

#### 3.3.4.2. Linear Model 2 (LM2)

LM2 (productivity ~ volume + slope + volume*slope) predicts harvester productivity as a function of tree volume, ground slope and the interaction effect of tree volume and ground slope. LM2 was subsequently tested through an ANCOVA table to determine if there was a significant interaction effect.

### 3.4. Cost calculation

The cost calculations were performed using the South African Harvesting and Transport Costing Model version 2.1.8 (Ackerman et al. 2016). This costing model is a Java based program for computers running a Windows operating system. The model caters for a variety of different machines as well as entire harvesting systems.

The majority of the costing inputs used in the model were provided by the contractor who owned the machines. The only cost item that was measured during the trial was the fuel consumption. Fuel cost was attained by recording the amount of fuel consumed each shift and subsequently calculating a mean hourly consumption for each machine. The mean hourly consumption is then multiplied by the current fuel price to attain a mean hourly fuel cost. The complete list of inputs required to utilise the model are detailed in Table 9. Once all necessary values have been entered, the programme outputs a number of different costs such as cost per month, cost per hour and cost per $m^3$. In this study cost in R/$m^3$ were used to represent the relative costs of both machine types.

Table 9: Costing components

| Item | **EBM** | **PBM** |
|---|---|---|
| Purchase price (PP), incl. attachments (Rand) | 3 500 000.00 | 6 000 000.00 |
| Expected economic life (EEL), (PMH) | 15 000 | 20 000 |
| Salvage value, (%) of PP | 15 | 10 |
| Insurance, (R/annum) | 100 000.00 | 150 000.00 |
| Fuel price, (R $l^{-1}$) | 13.00 | 13.00 |
| Fuel consumption, L $PMH^{-1}$) | 23 | 35 |
| Fuel cost, (R/ $PMH^{-1}$) | 299.00 | 455.00 |
| Oil and lubrication, (%) of fuel cost. | 15 | 8 |
| Maintenance and Repair (Rand) | 1 698 666.67 | 1 800 000.00 |
| Track set cost (Rand) | 120 000.00 | 200 000.00 |
| Track life(R $PMH^{-1}$) | 10 000 | 15 000 |
| Consumables (Rand $annum^{-1}$) | 9 564.00 | 12 864.00 |

# 4. Results

## 4.1. Height-DBH Relationship

In order to determine felled tree volumes, a sample of measured heights were used to develop the height and DBH relationship for the remaining trees harvested in this study. Figure 12 and Equation 4 show the function and curve that was used to estimate the unmeasured tree heights from the measured height-DBH pairs.

$$y = (7.2264)\ln(x) - 0.2212 \qquad \text{(Equation 4)}$$

| | | | | |
|---|---|---|---|---|
| Where: | y | = | Tree height | (m) |
| | X | = | Tree DBH | (cm) |
| | ln | = | Natural logarithm | |
| With: | $R^2$ | = | 0.7693 | |

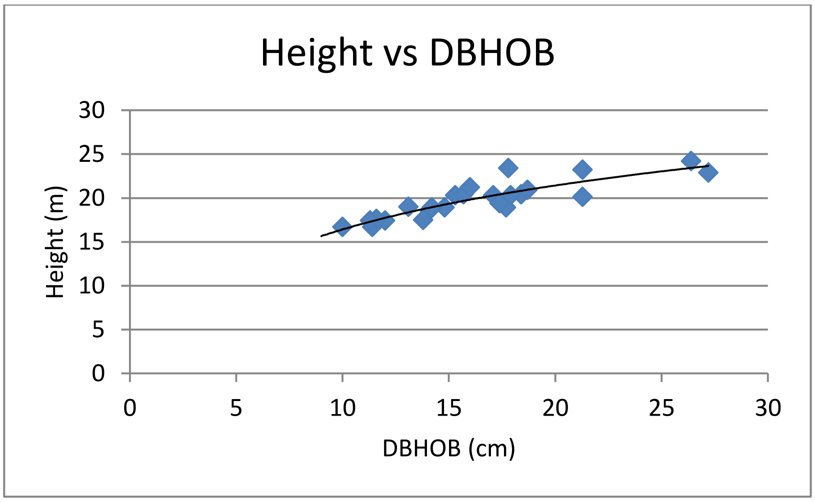


Figure 12: Height prediction curve

## 4.2. Mean tree volumes, harvest cycle times and machine productivity

Tables 9, 10 and 11 show the mean values for tree volume ($m^3$), total harvest time (min) per tree and actual productivity for both the EBM and PBM ($m^3.PMH^{-1}$).

### 4.2.1. Tree volume ($m^3$)

Table 10 shows that the PBM (range of tree volumes: $0.034m^3 – 0.477m^3$) was exposed to a greater range of tree volumes than the EBM ($0.038m^3 – 0.359m^3$) and the mean tree sizes (PBM = 0.147, EBM = 0.161) were found to be significantly different (p-value < 0.05). Although significantly different, the two mean tree sizes were within one standard deviation of each other and hence relatively similar for the purposes of this study.

Table 10: Tree volume statistics

| Machine | Mean ($m^3$) | Standard Deviation | Min Value ($m^3$) | Median Value ($m^3$) | Max Value ($m^3$) | Observations (n) |
|---|---|---|---|---|---|---|
| PBM | 0.147 | 0.069 | 0.034 | 0.139 | 0.477 | 428 |
| EBM | 0.161 | 0.061 | 0.038 | 0.159 | 0.359 | 436 |
| Difference | 0.014 | | | | | |

### 4.2.2. Total harvest time per tree (min.tree$^{-1}$)

The mean total time to fell and process a single tree for each machine is displayed below (Table 11). Note that the harvest time and productivity results include a mean movement time per tree. The mean movement time for the PBM was 0.165 min and the mean movement time for the EBM was 0.183 min (Figure 13). The mean movement time per tree for the PBM was 0.028 min.tree$^{-1}$ and the EBM mean movement time per tree was 0.026 min.tree$^{-1}$. With the movement times included this study found the PBM had a mean harvest and process time of 0.538 min.tree$^{-1}$ whilst the EBM had a mean time of 0.741 min.tree$^{-1}$.

Table 11: Total harvest time statistics

| Machine | Mean (min) | Standard Deviation | Min Value (min) | Median (min) | Max Value (min) | Observations (n) |
|---|---|---|---|---|---|---|
| PBM | 0.538 | 0.118 | 0.217 | 0.535 | 1.371 | 428 |
| EBM | 0.741 | 0.151 | 0.230 | 0.738 | 1.267 | 436 |
| Difference | 0.203 | | | | | |

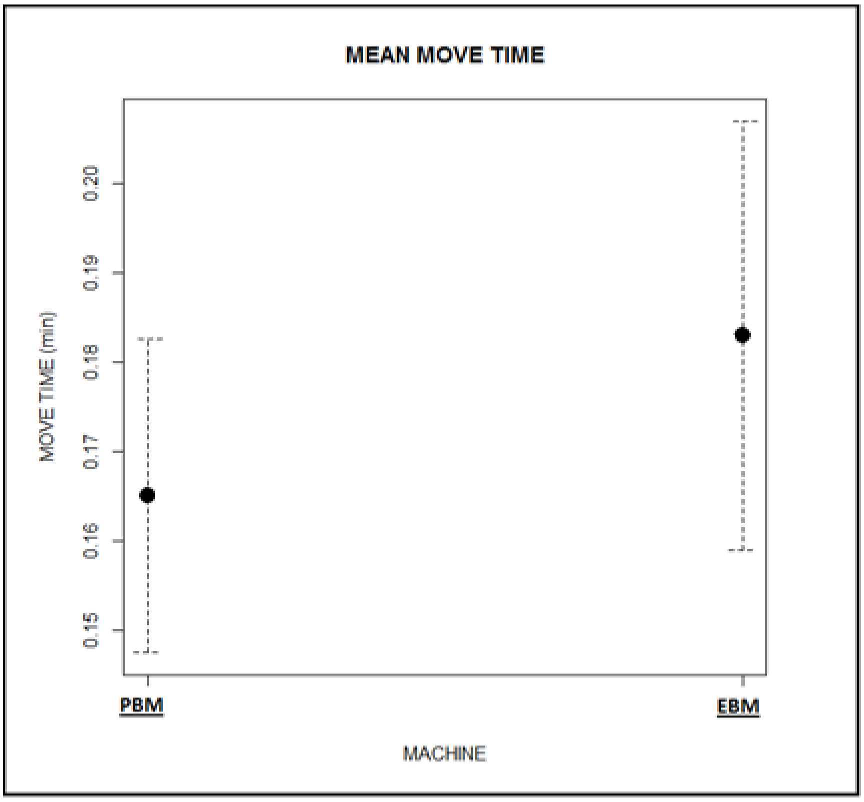


Figure 13: Mean move time for each machine

### 4.2.3. Productivity ($m^3.PMH^{-1}$)

The PBM was 3.24 $m^3.PMH^{-1}$ more productive over the course of the study with a mean productivity of 16.24 $m^3.PMH^{-1}$ versus the 13.00 $m^3.PMH^{-1}$ achieved by the EBM (Table 12). This difference was found to be statistically significant ($p < 0.05$) and is probably a slight under estimation of the actual difference as Table 9 shows that the PBM was working with trees of a smaller mean volume ($p < 0.05$).

Table 12: Productivity summary statistics

| Machine | Mean ($m^3.PMH^{-1}$) | Standard Deviation | Min Value ($m^3.PMH^{-1}$) | Median Value ($m^3.PMH^{-1}$) | Max Value ($m^3.PMH^{-1}$) | Observations (n) |
|---|---|---|---|---|---|---|
| PBM | 16.24 | 6.28 | 3.37 | 15.48 | 47.47 | 428 |
| EBM | 13.00 | 4.27 | 3.06 | 13.00 | 38.98 | 436 |
| Difference | 3.24 | | | | | |

The relationship between productivity and tree volume for both machines used in this study had a strong correlation and could account for approximately 75% of the variation in productivity (Figure

14 and 15; Equation 5 and 6). The productivity of the PBM is predicted from tree volume ($m^3.tree^{-1}$) using Equation 5 as follows:

$$Y = (0.0102)x^{(1.0676)} \qquad \text{(Equation 5)}$$

Where:

| | | | | |
|---|---|---|---|---|
| | Y | = | Productivity | ($m^3.PMH^{-1}$) |
| | X | = | Tree volume | ($m^3$) |
| With: | $R^2$ | = | 0.7889 | |

The productivity of the EBM is predicted from tree volume using Equation 6 as follows:

$$Y = (0.0072)x^{(1.0702)} \qquad \text{(Equation 6)}$$

Where:

| | | | | |
|---|---|---|---|---|
| | Y | = | Productivity | ($m^3.PMH^{-1}$) |
| | X | = | Tree volume | ($m^3$) |
| With: | $R^2$ | = | 0.7531 | |

Figure 14 and Figure 15 display the actual spread of the data used to develop Equation 5 and 6 respectively. Figure 16 displays the true means of productivity for the respective machines.

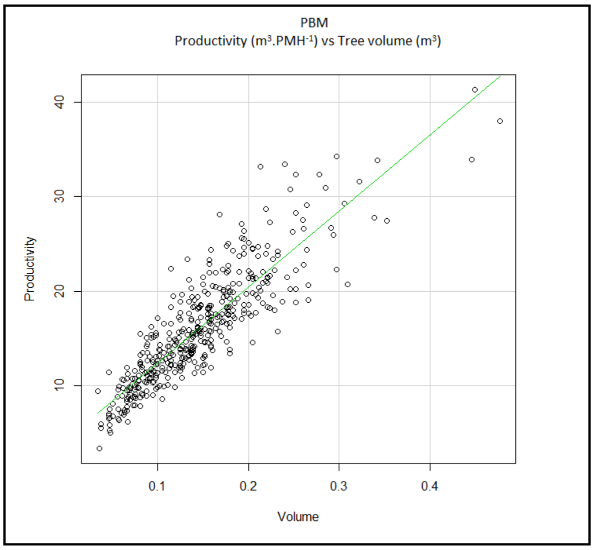


Figure 14: PBM scatterplot of productivity ($m^3.PMH^{-1}$) vs tree volume ($m^3$)

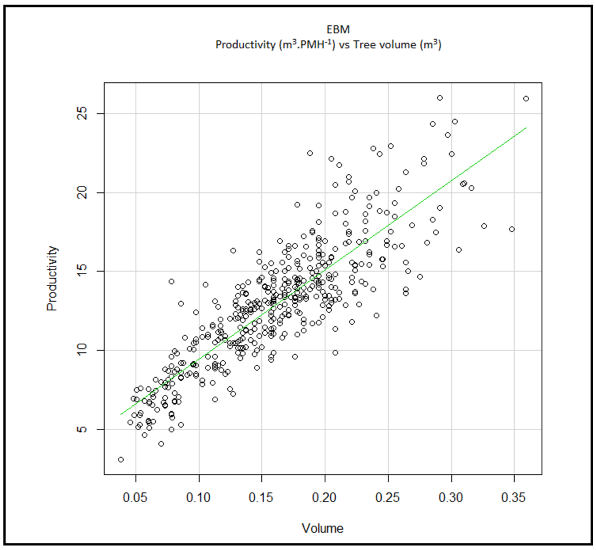


Figure 15: EBM scatterplot of productivity ($m^3.PMH^{-1}$) vs tree volume ($m^3$)

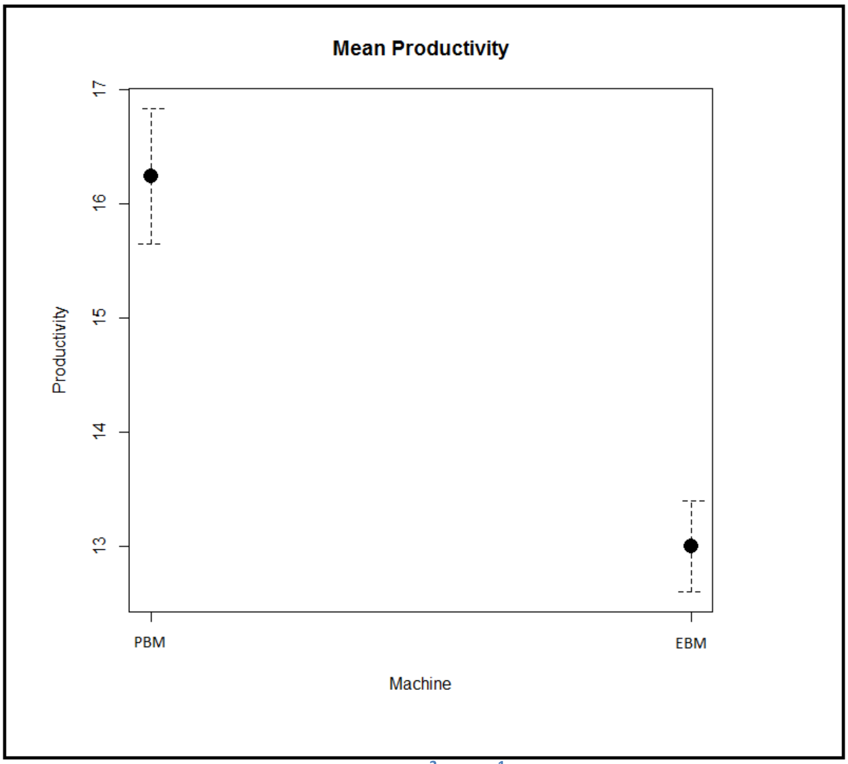


Figure 16: Mean productivity ($m^3.PMH^{-1}$) of both machines

## 4.3. Slope

Slope values (%) for each tree were paired with the production rates associated with the tree in order to quantify the effects of slope on productivity. These values are used to create the generalised linear models for predicting productivity that were described in Chapter 3. The models are run through an ANOVA and ANCOVA analyses to determine if the slope had a significant effect on the productivity of either machine. Table 13 shows the basic slope statistics for each machine. The PBM worked on an average slope of 26.08% whilst the EBM worked on an average slope of 23.97%. The difference is not significant ($p > 0.05$).

Table 13: Slope summary statistics

| Machine | Mean (%) | Standard Deviation | Lowest Value (%) | Median Value (%) | Highest Value (%) | Observations (n) |
|---|---|---|---|---|---|---|
| PBM | 26.08 | 4.55 | 15 | 25.60 | 39.40 | 428 |
| EBM | 23.97 | 8.07 | 4 | 19.25 | 36.00 | 436 |

The generalised linear models developed in this study were tested with ANOVA and ANCOVA analysis and yielded the following results.

### 4.3.1. ANOVA of [productivity = slope + volume] linear models

Figure 17 represents the simple main effect of slope on the productivity of the EBM as described by LM1. The EBM mean tree size (0.161 $m^3$) was used to generate Figure 18.

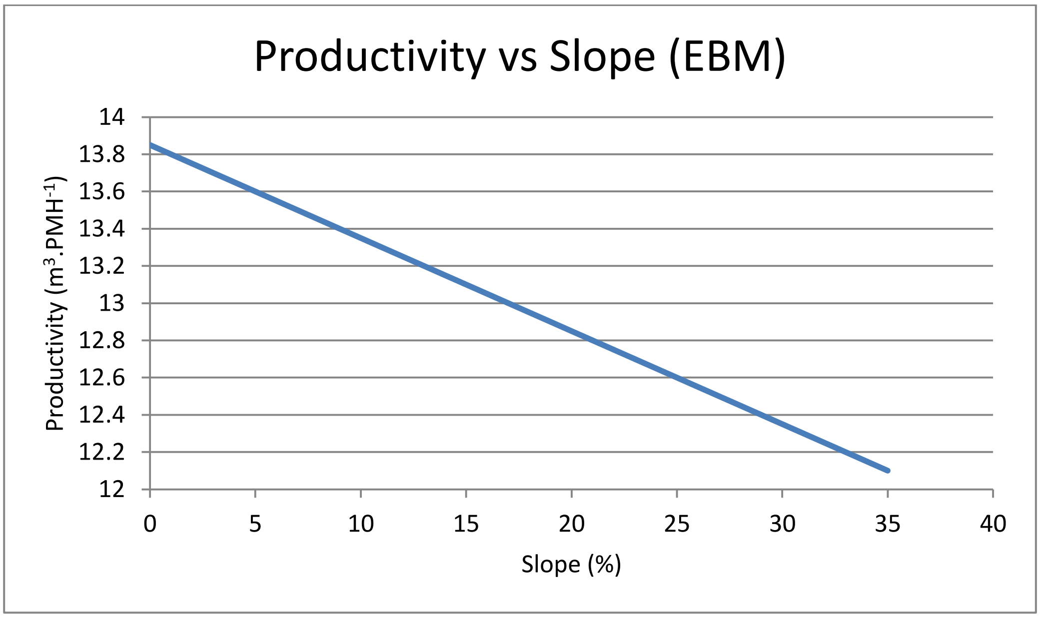


**Figure 17: Productivity as a function of slope for EBM**

The results shown in Tables 14 and 15 indicate that the productivity of the EBM was negatively affected by an increase in slope encountered. It can be stated with 95% confidence that for every percentage unit of slope increase a decrease in productivity of 0.048$m^3$.$PMH^{-1}$ ($p < 0.05$) can be expected.

**Table 14: EBM Linear Model 1 Results**

| **EBM** | Estimate | Std.Error | T-value | Probability of (>\|T\|) | Significance |
|---|---|---|---|---|---|
| Intercept | 4.89822 | 0.47343 | 10.346 | < 2 $x10^{-16}$ | *** |
| Slope (%) | -0.04803 | 0.01472 | -3.264 | 0.00119 | ** |
| Volume ($m^3$) | 57.38591 | 1.94301 | 29.535 | < 2 $x10^{-16}$ | *** |

Where:

| | |
|---|---|
| Residual standard error: | 2.46 on 433 (DF) |
| Multiple R-squared: | 0.669 |
| Adjusted R-squared: | 0.667 |
| F-statistic: | 437.5 on 2 and 433 DF |
| p-value: | < 0.05 |

Equation (3) which describes LM1 is populated with coefficients as follows:

$$Productivity = (57.386)Volume + (-0.048)Slope + (4.898) \qquad \text{(Equation 3)}$$

With:

Productivity in ($m^3.PMH^{-1}$)

Volume in ($m^3$)

Slope in (%)

**Table 15: EBM ANOVA Results**

| **EBM** | Sum of Squares | Degrees of freedom | F-value | Probability of (>F) | Significance |
|---|---|---|---|---|---|
| Slope (%) | 64.4 | 1 | 10.652 | 0.001187 | ** |
| Volume ($m^3$) | 5276.8 | 1 | 872.291 | $< 2.2x10^{-16}$ | *** |
| Residuals | 2619.4 | 433 | | | |

The slope and volume effect plots for the EBM (Figure 18 and Figure 19) are used to give a graphical representation of the linear relationships between slope and productivity as well as the relationship between volume and productivity as described by LM1. A narrow buffer indicates a strong correlation and a high degree of estimation accuracy. A broad buffer indicates a weak correlation and a lower degree of estimation accuracy, implying that a narrow buffer around the line depicts a strong, predictable relationship between slope or tree volume and productivity.

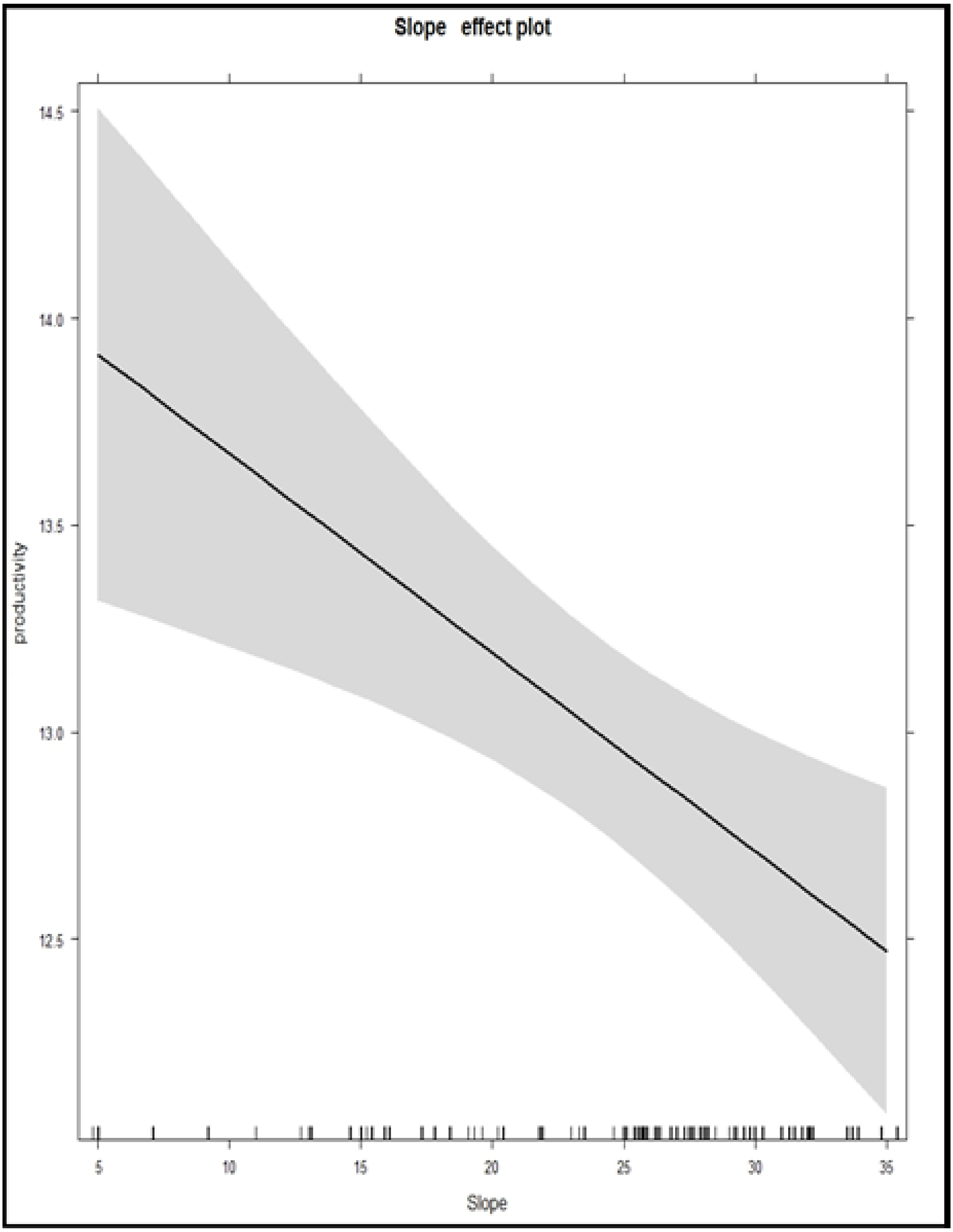


Figure 18: Slope effect plot (EBM)

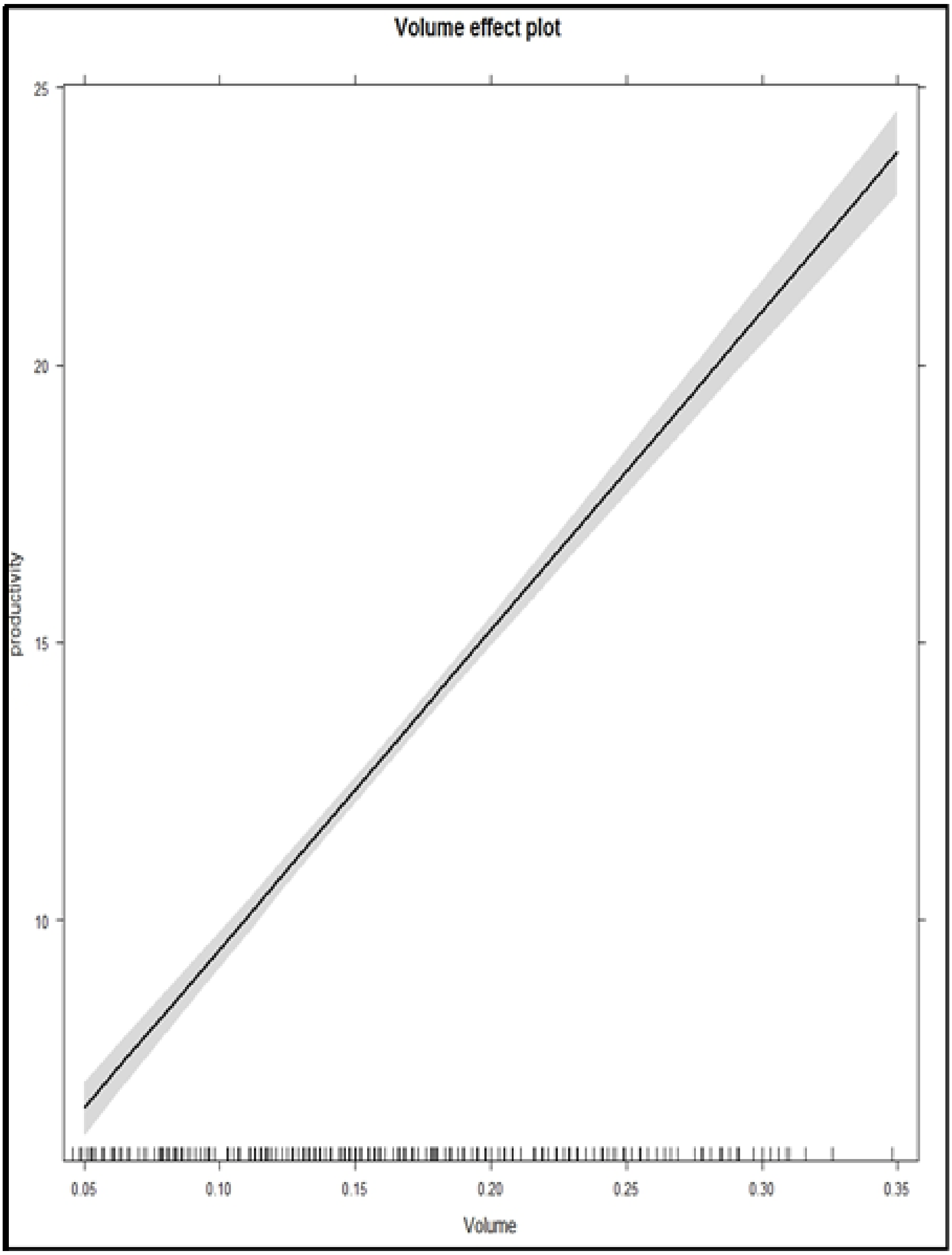


Figure 19: Tree Volume effect plot (EBM)

From the results shown in Tables 16 and 17 it is clear that the PBM is not significantly affected by the change in slope encountered in this study. However tree volume was found to be highly significant in determining productivity.

**Table 16: PBM LM1 basic statistics**

| **PBM** | Estimate | Std.Error | T-value | Probability of (>\|T\|) | Significant |
|---|---|---|---|---|---|
| Intercept | 4.790967 | 1.002743 | 4.778 | 2.44 $\times 10^{-06}$ | *** |
| Slope (%) | 0.005877 | 0.035806 | 0.164 | 0.87 | NS |
| Volume ($m^3$) | 76.864974 | 2.364164 | 32.513 | < 2 $\times 10^{-16}$ | *** |

With:

Residual standard error: 3.369 on 425 DF

Multiple R-squared: 0.7134

Adjusted R-squared: 0.712

F-statistic: 528.9 on 2 and 425 DF

p-value: < 0.05

**Table 17: PBM ANOVA Results**

| **PBM** | Sum of Squares | Degrees of freedom | F-value | Probability of (>F) | Significant at 0.05 level |
|---|---|---|---|---|---|
| Slope (%) | 0.3 | 1 | 0.0269 | 0.8697 | NS |
| Volume ($m^3$) | 11998.7 | 1 | 1057.0652 | <2 $\times 10^{-16}$ | *** |
| Residuals | 4824.1 | 425 | | | |

Figures 20 and Figure 21 display the slope and productivity effect plots for the PBM. From the broad spread around the mean slope effect it is clear that there is no discernible or significant relationship between the productivity of the machine and the slope of the terrain it is operating on.

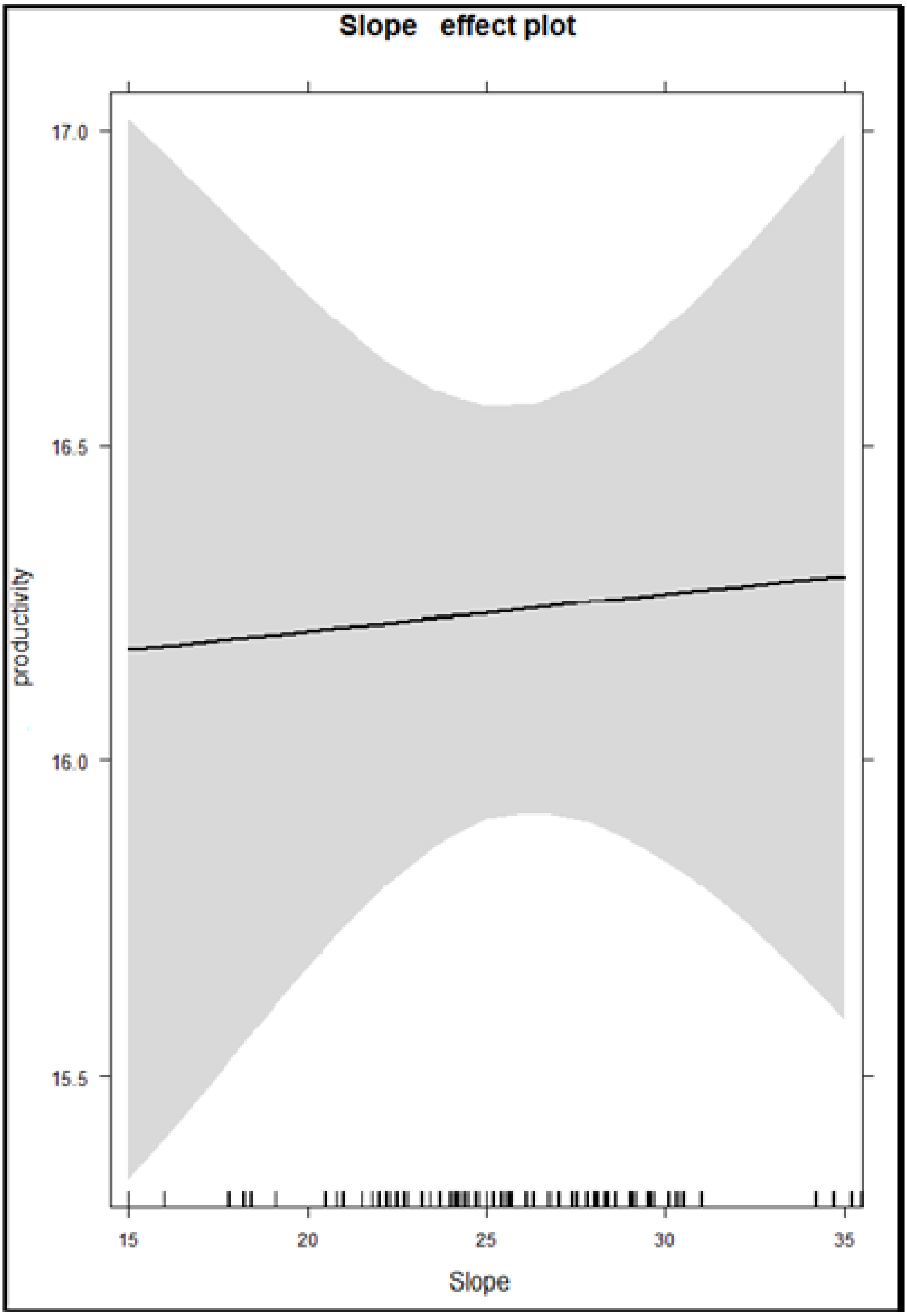


Figure 20: Slope effect plot (PBM)

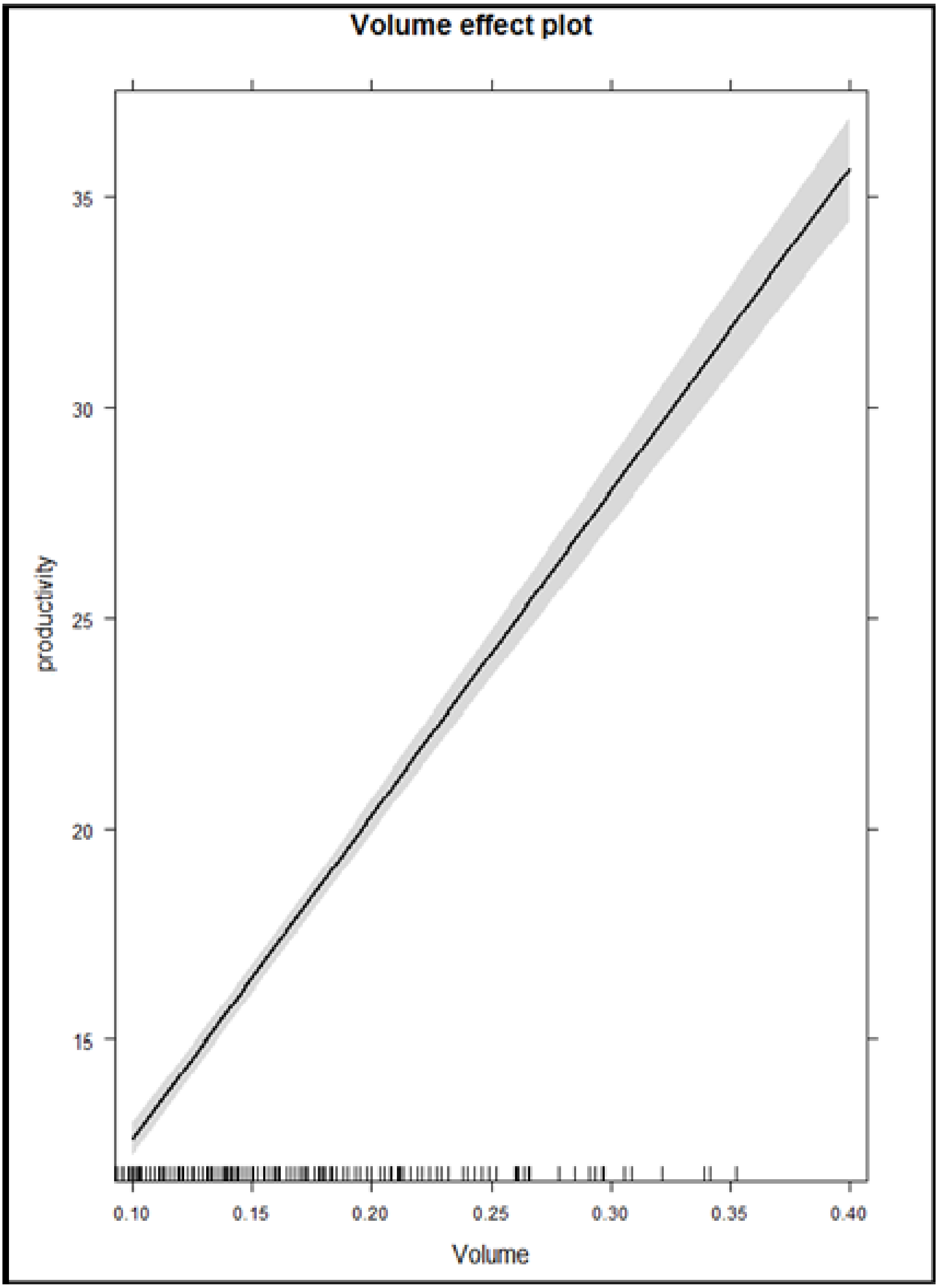


Figure 21: Tree volume effect plot (PBM)

#### 4.3.2. ANCOVA of [productivity = slope + volume + (slope x volume)] linear model

The analysis of co-variance, to determine if there was any interaction effect between slope and volume on productivity, yielded the results shown in Table 19 (EBM) and Table 21 (PBM).

**Table 18: EBM Linear Model 2 basic statistics**

| EBM | Estimate | Std.Error | T-value | Probability of (>\|T\|) | Significant |
|---|---|---|---|---|---|
| Intercept | 4.73667 | 1.06827 | 4.434 | $1.17 \times 10^{-05}$ | *** |
| Slope (%) | -0.04130 | 0.04253 | -0.971 | 0.332 | NS |
| Volume ($m^3$) | 58.44977 | 6.59798 | 8.859 | $< 2 \times 10^{-16}$ | *** |
| Slope x vol | -0.04403 | 0.26092 | -0.169 | 0.866 | NS |

With:

| | |
|---|---|
| Residual standard error: | 2.462 on 432 DF |
| Multiple R-squared: | 0.669 |
| Adjusted R-squared: | 0.6667 |
| F-statistic: | 291 on 3 and 432 DF |
| p-value: | < 0.05 |

The results of the ANCOVA to test for co-variance between slope and volume in the case of the EBM indicated no significant interaction effect between slope and volume at the 95% confidence level ($p > 0.05$).

**Table 19: EBM ANCOVA table**

| EBM | Sum of Squares | Degrees of freedom | F-value | Probability of (>F) | Significant at 0.05 level |
|---|---|---|---|---|---|
| Slope (%) | 4.89822 | 1 | 10.6284 | 0.001202 | ** |
| Volume ($m^3$) | -0.04803 | 1 | 870.3338 | $< 2.2 \times 10^{-16}$ | *** |
| Slope x vol | 57.38591 | 1 | 0.0285 | 0.866079 | NS |
| Residuals | 2619.2 | 432 | | | |

Table 20 displays the summary statistics of the PBM LM2 which is used to determine if there is an interaction effect between the slope and volume variables.

**Table 20: PBM Linear Model 2 summary statistics**

| PBM | Estimate | Std.Error | T-value | Probability of (>\|T\|) | Significant |
|---|---|---|---|---|---|
| Intercept | 4.47612 | 2.28761 | 1.957 | 0.051 | NS |
| Slope (%) | 0.01787 | 0.08614 | 0.208 | 0.836 | NS |
| Volume ($m^3$) | 79.14764 | 15.08978 | 5.245 | $2.47 \times 10^{-07}$ | *** |
| Slope x Volume | -0.08686 | 0.56710 | - 0.153 | 0.878 | NS |

Where:

| | |
|---|---|
| Residual standard error: | 3.373 on 424 DF |
| Multiple R-squared: | 0.7134 |
| Adjusted R-squared: | 0.7114 |
| F-statistic: | 351.8 on 3 and 424 DF |
| p-value: | < 0.05 |

The results of the ANCOVA to test for co-variance between slope and volume in the case of the PBM also indicated no significant interaction effect between slope and volume ($p > 0.05$). And again the individual tree volume was the most significant variable in terms of predicting productivity rates for the PBM.

**Table 21: PBM ANCOVA table**

| PBM | Sum of Squares | Degrees of freedom | F-value | Probability of (>F) | Significant |
|---|---|---|---|---|---|
| Slope (%) | 0.3 | 1 | 0.0269 | 0.8698 | NS |
| Volume ($m^3$) | 11998.7 | 1 | 1054.6363 | $<2 \times 10^{-16}$ | *** |
| Slope x Volume | 0.3 | 1 | 0.0235 | 0.8783 | NS |
| Residuals | 4823.9 | 424 | | | |

The lack of significant interaction effect for both the EBM and PBM means that the LM1 models and equations for both machines can be used to draw inferences on the results of the study.

## 4.4. Costing

Figure 22 represents the effect of the ground slope encountered by the EBM on the unit cost of felling and processing each $m^3$ of timber. This measure of cost fluctuation is derived from the change in productivity caused by the slope, again using the EBM mean tree size (0.161 $m^3$). This figure shows that an increase in slope leads to an increase in unit costs with respect to the EBM. The relationship is linear due to the fluctuations in cost being directly proportional to the change in productivity.

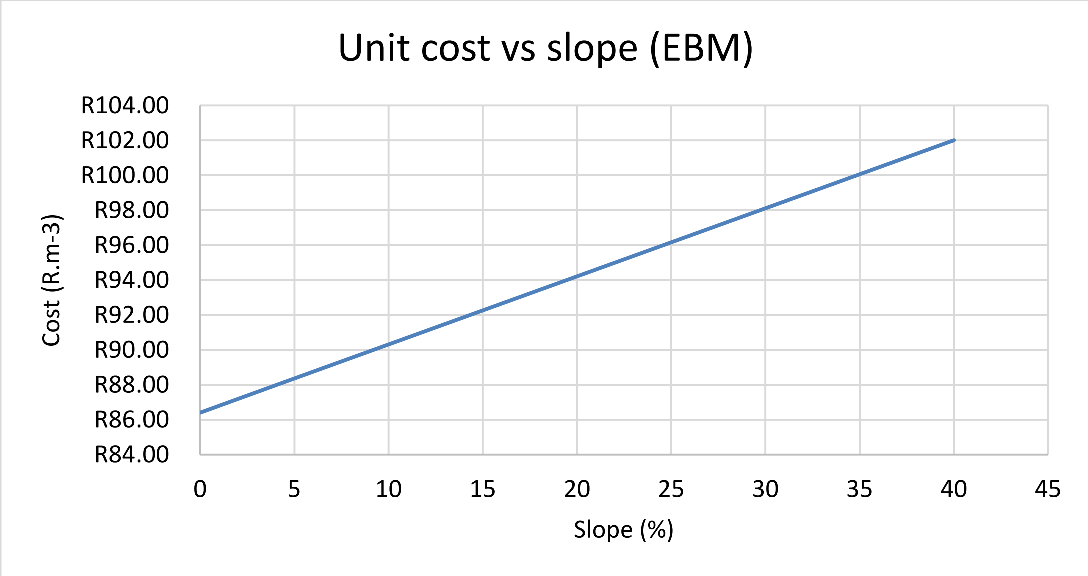


Figure 22: Unit costs vs slope of EBM

Figure 23 plots the effects of slope against productivity as well as unit cost to show how unit costs rise as productivity falls when faced with increasingly steep slopes.

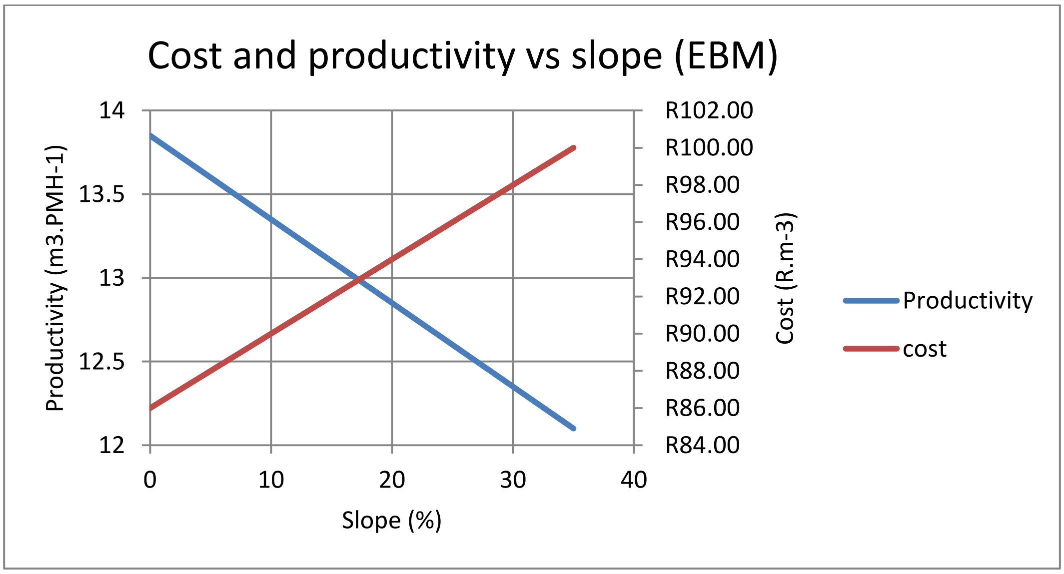


Figure 23: Cost (R.m$^{-3}$) and productivity (m$^{3}$.PMH$^{-1}$) vs slope (%) for EBM

Figure 24 displays the theoretical linear relationship between costs and productivity for the PBM in this study. The relationship is linear because the method of calculating fluctuations in costs is based solely on the change in productivity as all the other costing inputs remain constant. This means that the change in costs is directly proportional to the change in productivity.

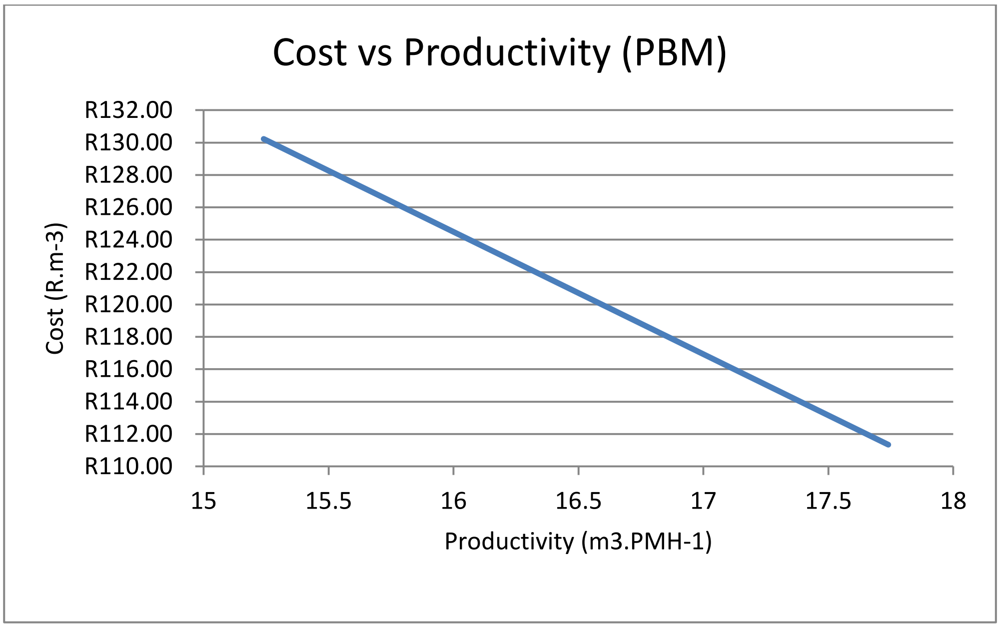


Figure 24: Unit cost vs productivity for PBM

### 4.4.1. Machine cost comparison

Table 23 displays the difference in mean unit costs of the two machines whilst operating in the study. At R122.67 per $m^3$, the PBM had a 30% higher mean harvesting cost than the EBM's mean of R94.46 per $m^3$. Due to the slope having no influence on the productivity of the PBM and because the influence of slope on fuel consumption could not be measured, it is assumed that the fuel consumption is constant across the range of slopes. Therefore any variation in unit cost of harvesting with the PBM is primarily determined by the productivity of the machine which in turn is determined by tree size. The unit cost of harvesting with the EBM varied based on slope from approximately R86.00 per $m^3$ in the flattest areas of the study to R100.00 per $m^3$ in the steepest areas.

Table 22: Total cost comparison

| Object | Mean cost/unit |
|---|---|
| Excavator based machine (1) | R 94.46.$m^{-3}$ |
| Purpose built machine (2) | R 122.67.$m^{-3}$ |
| Difference (1-2) | (-) R 29.21.$m^{-3}$ |

# 5. Discussion

## 5.1. Productivity comparison

The results of this study show that the PBM had a higher overall mean productivity than the EBM over the course of the entire study. This is despite the fact that the PBM was working with a slightly smaller mean tree size, which is according to literature is a major factor in determining productivity (Alam et al. 2012; Ghaffariyan et al. 2012; Ramantswana et al. 2012; Spinelli & Magagnotti 2010; Spinelli et al. 2002; Spinelli & Magagnotti 2013; Ramantswana et al. 2013). The results of this study confirmed tree size to be most significant variable in terms of predicting productivity for both of the machine types studied (EBM and PBM).

Eriksson & Lindroos (2014) found mean productivity to be $18m^3.PMH^{-1}$ when using a machine of similar size and configuration to the EBM and working with a similar mean tree volume of $0.160m^3$. The data collected in this study showed the EBM was working with a mean stem size of $0.161m^3$ and achieved a mean productivity of $13m^3.PMH^{-1}$. This is significantly lower in comparison with the results of Eriksson & Lindroos (2014), it is possible that the effect of the slopes encountered by the EBM may have contributed to this difference due to the lower productivity achieved on the steeper slopes. Eriksson and Lindroos (2014) did consider slope but due to the large non-uniform dataset that they used, some of the machines did not have slope effects and the ones that did were insignificant in the prediction models. The PBM was working with a mean tree size of $0.147m^3$ and achieved a mean productivity of $16.2m^3.PMH^{-1}$. Eriksson & Lindroos (2014) produced results of $17m^3.PMH^{-1}$ under similar conditions. Both machines observed in this study had a lower mean productivity than the equivalent machine in the study by Eriksson & Lindroos (2014), however the PBM was within one standard deviation of its counterpart.

The differences in productivity found between the EBM and PBM in this study conform to the expected differences as outlined in the literature review. The lower productivity achieved by the EBM, even in the flat areas, suggests that the hydraulic systems and machine design limited the EBM's ability to compete with the PBM and its forestry specific design.

## 5.2. Slope

### 5.2.1. Measurement

The development of LiDAR, GPS and GIS software have all reduced the time and effort required for terrain slope measurement and should promote further studies concerning slopes and the effect they have on forest operations (Lin & Hyyppa 2012).

Measuring slope as a continuous variable allows for more precise estimation of slope effects and gives a better understanding of the impact of slight changes in slope experienced by the machines. Slope classes have been useful in the past and will probably continue to be commonly used throughout the industry (Berkett 2013), but as LiDAR equipment and data become more accessible there will be no reason to continue with slope classes when researchers have the means to collect significantly more precise data. This is already happening as we see many companies in the industry investing in LiDAR equipment or contracting out to specialists (Strandgard et al. 2014).

### 5.2.2. Effect on productivity

Slope was shown to have a negligible, if any effect on the productivity of the PBM. The EBM on the other hand was significantly affected by the degree of slope encountered in its work environment. The strong adjusted co-efficient of determination ($R^2$ = 0.78) of the regression model for predicting productivity from tree volume and slope suggests that the model should produce relatively accurate and precise predictions. Of the variation described by the EBM LM1, the slope variable itself only accounted for approximately 4%, tree size accounted for approximately 74% and the remaining 22% was from an unknown source (error variable). In this study this translated to an average decrease in productivity of 0.048$m^3$.$PMH^{-1}$ for every 1% increase in slope (Figure 17). The results of Brown et al. (2013) showed a decrease of 24% in levelling harvester productivity between 5%-19% and 20%-51% slopes. FPInnovations (2008) found a reduction in productivity of 30% between 10% - 19% slope and (20% – 33%) slope based on modelled results from a number of different purpose built feller-buncher studies. Strandgard et al. (2014) found no significant change in productivity between slopes of 19% to 35% and 36% to 50% when studying a levelling processor only.

In order to compare the results of this study with the existing literature it is necessary to calculate a mean productivity for each class range utilised in the literature (Table 24 and Table 25). This is done by aggregating all the productivity data for each range and then calculating the means for each class. As the effect of slope on productivity has been illustrated through a percentage change in the literature, Table 24 and Table 25 show the lower range class as 100% productivity and the productivity in the higher range class is then depicted as a percentage relative to the productivity achieved in the lower class. For instance, in Table 24 the higher slope range of Brown et al. (2013) is displayed as 76%, this means that the mean productivity dropped by 24% from the lower slope range to the higher slope range.

Table 23: Comparison of slope effect results with Brown et al., (2013)

| Study | Slope class | |
|---|---|---|
| | (5% - 19%) | (20% - 51%) |
| Brown et al. (2013) | 100% | 76% |
| This study | 100% | 95% |

Brown et al., (2013) found that productivity decreased by 24% when harvesting in the steeper slope class 20% - 51%. The comparative results of this study show a 5% decrease in productivity when moving to the steeper slope class. The range of the steeper slope class used by Brown et al., (2013) goes beyond the extent of slopes experienced in this study. This may have contributed to the discrepancy in results as the machines studied by Brown et al., (2013) were exposed to more extreme slopes than those encountered by the machines in this study.

Table 24: Comparison of slope effect results with FPInnovations (2008)

| Study | Slope class | |
|---|---|---|
| | (10% - 19%) | (20% - 33%) |
| FPInnovations (2008) | 100% | 70% |
| This study | 100% | 95% |

FPInnovations (2008) found that productivity decreased by 30% when harvesting in the steeper slope class 20% - 33%. The results from this study again show a 5% decrease in productivity when moving to the steeper slope class. It is important to note that the reason the decrease in productivity for this study is constant at 5% whilst the range of the slope class has changed significantly (20% – 33% versus 20% - 51%), is due to the slopes in this study rarely exceeding 35%. And hence the majority of the data comes from the lower end of the slope class used by Brown et al., (2013). This means that although the range of the class used by Brown et al., (2013) was wider than that of FPInnovations (2008), there was no data to utilise beyond the upper level of the FPInnovations (2008) steeper class range.

### 5.3. Machine selection and costs

Although the results show that the PBM was significantly more productive than the EBM and was not negatively affected by increasing slope as with the excavator, it does not necessarily stand out as the most efficient option. The main reason for this is because the cost of owning and operating the PBM is much higher than the equivalent EBM. In this case the PBM was a particularly old machine with approximately 18 000 hrs compared with 12000 hrs for the EBM, which may have contributed to the high variable cost. The capital outlay of 60% more than the EBM combined with the significantly higher running costs means the productivity of the PBM needs to be higher in order for the two machines to be on a level footing from the outset. The EBM is more than adequate for most situations found in the area, but there are areas with trees planted for harvesting that are beyond the EBM's slope safety limits and capabilities. In these cases the PBM must be used or motor-manual harvesting with chainsaws will need to be employed. This means that despite the differences in costs and production rates, the situation will dictate the need for using specialised PBM's over EBM's.

Figure (24) shows the effect of the differences in productivity due to changes in slope, and how that affects unit costs for the EBM. Because the PBM was not significantly affected by the changes in slope that it experienced it is assumed that the costs were constant (at R122.67) with regard to slopes encountered during harvesting. From the data collected in this study, even at the most extreme slopes experienced by the EBM, the unit costs of harvesting were always lower when using the EBM.

# 6. Conclusion

The objective of this study, to determine whether there is a relationship between the slope on which PBM and EBM are expected to work and the productivity and cost of these machines, was achieved. This study has shown that the productivity of the excavator based machine is significantly influenced by the slope the machine is experiencing during harvesting. An increase in slope leads to a decrease in productivity (1% increase in slope equates to a $0.048m^3.PMH^{-1}$ decrease in productivity). The levelling PBM is not significantly influenced by the degree of slope that the machine is experiencing, at least in terms of the slopes encountered in this study (0% - 50%). However the benefits of the PBM do not significantly outweigh the burden of extra costs carried along with the machine. This is dependent on the specific machine and situation.

The results of this study suggest that the EBM, which has a cost range of $R86.22\ .m^{-3}$ to $R102.34.m^{-3}$ depending on slope is more cost efficient than the PBM ($R122.67\ .m^{-3}$) when harvesting in terrain that does not exceed the safety guideline of 35% - 40% slope. This makes the debate of machine selection somewhat incidental as the PBM is necessary for terrain which eliminates the possibility of using the EBM. More research should be done to assess the relevance of the slope limits in place. The data from this study suggests that the EBM will at some point become more expensive than the purpose built machines as the slope increases beyond 35%.

The models developed in this study could be used by a contractor or company to assess the expected production rates prior to the commencement of an operation, provided that the conditions were similar to those found in this study. This would then allow for more accurate project costing and overall improved efficiency.

Future research on the relationship between harvester productivity and ground slope should incorporate LiDAR data and view slope as a continuous variable instead of using slope classes. In order to obtain meaningful results, future studies should consider a greater number of machines across various conditions with a set group of operators interchanging between machines to get a better understanding of the true variance between the two machine types, EBM and PBM. Further research in this field should also consider investigating whether there is a mechanical/machine related reason slope would affect machine productivity because without a reasonable explanation for the machine not being able to perform optimally on slopes the only other source of variation lies with the machine operator.

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